AN EXPERIMENTAL ANALYSIS OF SWIMMING POOL DESIGN

by

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Signature of Author . . . .

Department of Civil Engineering, May 19, 1938

Signature of Professor in
Charge of Research . .

Signature of Chairman of Department
Committee on Graduate Students . . . .

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Cambridge, Mass.

May 9, 1938

Professor George W. Swett

Secretary of the Faculty

Massachusetts Institute of Technology

Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the degree of Master of Science, this thesis is submitted for the consideration of the Department Committee on Graduate Students. This work, on the experimental study of swimming pool design, was carried out with the aim of settling certain questions of interest to the Institute, and of determining a rational experimental approach to further studies of the same kind. In this report will be found much of the information which was specifically desired, as well as data and suggestions which should be of value to anyone wishing to continue experimental work on the hydraulic design of swimming pools.

Respectfully submitted,

Thomas H. Campbell

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PART I.

SUMMARY OF OBJECTS AND CONCLUSIONS

The object of these experiments was to determine:

1. Means of making a swimming pool as quiet as possible; in other words, of eliminating the waves caused by any disturbance as rapidly as possible.
2. Means of thoroughly mixing the incoming disinfected water, which contains a small amount of latent disinfectant, so that no spots of local contamination will be obtained in the swimming pool.
3. A rational experimental approach to similar studies, to aid in furthering other work of this nature.

The results of the tests herein described indicate that:

1. The quietest swimming pool is one with:
   (a.) A bottom with a broken longitudinal slope.
   (b.) Overflow gutters which immediately drain the wash, allowing none to splash back into the pool.
   (c.) Floating lane markers tightly strung between the ends.
2. Satisfactory mixing is obtained with the simple, conventional circulation system.
3. The methods described in this report are entirely satisfactory for experimental work of this kind, although they are yet rough and admit of many improvements.

PART II

PREVIOUS EXPERIMENTAL WORK ON SWIMMING POOL DESIGN

A brief search through the Institute library, and the questioning of several swimming pool managers and coaches revealed no previous experimental work of this kind with the exception of one known case in which dye was injected into a pool to determine the extent of mixing of incoming water. This experiment was evidently superficial, and apparently no recorded data were left for reference.

PART III

THEORETICAL CONSIDERATIONS

1. Wave Action

The study of wave action was made to determine the rate of subsidence of waves in a pool under various controlled conditions. It is generally acknowledged by authorities that the less wave disturbance there is in a pool, the faster it is possible for a person to swim.

Observations made at various pools while they were in use showed that there are two kinds of waves which cause interference to a swimmer. One is the wave which is generated by diving, and which quickly disturbs the entire surface of the pool. The other is a wave which travels in front of the swimmer and may interfere with him at the end of the pool by reflecting back toward him.

Practical considerations indicated that little would be gained by a study of the latter type. Therefore this report confines itself to experiments made on the wave generated by a person diving, and methods of quieting the wave as efficiently as possible.

The first tests indicated that it was impractical to try to simulate a person diving. An object which was large enough to generate the proper size of wave was found to be too bulky to be of practical use. However, it may be reasoned that no matter how the wave may be generated, its rate of subsidence is a reliable indication of the rate of subsidence of any similar wave generated under similar time and space conditions.

Referring to a text on fluid physics*, it was found that although long waves travel more rapidly than short ones, waves may be superposed on each other without much disturbance unless the pool is so shallow that the depth effect becomes of considerable importance. Assuming that the law of superposition applies, it follows that a study of the subsidence of one wave is a direct measure of the quietness of the pool. Actually, in this study, it was found that the waves were being affected by the depth to some extent.

The experimental results herein quoted are all based on a standard wave generated by revolving a board 12" long, and projecting 3" into the water throughout its length, about one end as an axis through an arc of 90° in one corner of the pool in the time of one second. Preliminary tests gave consistent results by the use of this wave. The rate of subsidence of the resulting wave was considered a measure of the relative quietness of the pool under the conditions being studied. The curves and other data given in this report are to be considered qualitatively only; never quantitatively except under identical conditions.

It was originally intended that the effect of gutter section should be studied in some detail. However, it soon

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* "The Physics of Solids and Fluids" by Ewald, Pöschl & Prandtl.

became evident that such a study was not practical with the equipment which was used in these experiments. This report confines itself to comparing the case of a pool with no gutters with that of a pool with sharp crested weirs for gutters. In the opinion of the writer, these weirs are entirely comparable to the "roll-out", or any similar type of gutter where the water spills freely over the gutter crest, if the water is immediately drained from the gutter and not allowed to splash back into the pool. After visiting and observing many pools in use, and after careful study of the model pool herein described, the writer believes that the above type of gutter gives the maximum subsidence of waves, if water is continually flowing over the gutter lip.

In the model tests in which the weirs were in action, an 8-hour turnover was simulated. One quarter of the incoming water was allowed to flow over the weir crests. The remainder was drained through the outlet valves in the bottom of the pool. Since wave action is being studied, gravity forces predominate, and Froude's law governs the rate of flow in the model. By this law, the ratio of quantities:

$$\frac{Q_m}{Q} = \left(\frac{L_m}{L}\right)^{2.5}$$

where Q_m and Q are rates of discharge in the model and the prototype, respectively; and L_m/L is the ratio of a given dimension in the model and prototype, respectively, or 1/8.

$$Q_m = Q\ (1/8)^{2.5}$$

Considering a prototype section 50' wide, 82' long, with an average depth of 8'; for an 8-hour turnover:

$$Q_m = \frac{(50)(82)(8)}{(8)(3600)}(1/8)^{2.5} = 0.0063 \text{ cfs.}$$

which is the quantity which was delivered to the pool during the wave tests with the weirs in action.

2. Mixing of Incoming Water.

The water which is delivered to the pool has been disinfected, and should retain some latent disinfectant properties so as to keep the entire pool from contamination in spite of the continual addition of harmful bacteria. Therefore, thorough mixing of the water is desired.

In this study, dye was injected into the incoming jet of water, and the manner of mixing was noted. Viscous forces were considered to be those of most importance, so that Reynold's model law applied. The ratio of quantities:

$$\frac{Q_m}{Q} = \frac{L_m}{L}\frac{\nu_m}{\nu}$$

where the symbols are as in the previous derivation except that ν_m and ν are the kinematic viscosities of the fluids in the model and prototype, respectively. Since the temperature of the water in the model was not much different than that in swimming pools, ν_m was considered equal to ν, so that for an 8-hour turnover:

$$Q_m = (1/8)Q = \frac{(50)(82)(8)}{(8)(3600)(8)} = 0.143 \text{ cfs.}$$

However, it proved impossible to obtain this rate of discharge from the source of supply. It was just possible to obtain 0.127 cfs., so that a 9-hour turnover could be duplicated. Tests were run using 9-hour, 16-hour, and 24-hour turnovers.

While the injected dye distribution may not properly simulate the effect of contamination of the incoming stream of disinfected water, the observed conditions of mixing were considered indicative of the efficiency of the injector system.

It was also desired to determine the effect of swimmers upon the mixing of the water. It was estimated that the average swimmer may travel at the rate of two feet per second. As above, viscous forces govern, and if the kinematic viscosities of prototype and model fluid are equal, the model law states that:

$$V_m L_m = VL$$

where L and L_m are corresponding lengths in prototype and model, and V and V_m are corresponding velocities. Hence the velocity of a swimmer in a 1:8 scale model would be:

$$V_m = (2)(8/1) = 16 \text{ feet per second.}$$

A swimmer was simulated by towing a piece of 2x4 timber 10" long the length of the pool in one second, or at a velocity of 10 feet per second. A higher velocity could not be obtained , due to practical limitations.

PART IV

PROCEDURE

1. Method of Attack.

As the most important questions to be answered were those dealing with the elimination of excess wave conditions in the pool, this was the first problem taken up.

There was no precedent to follow, since no previous work of this kind could be found. The initial step was, therefore, to determine methods of approach, and the limitations of the apparatus.

The effect of gutter design on wave subsidence was the first problem to be considered. In order to determine the practicability of a study of this problem in the model pool, and to find what range of experimental values might be expected, it was decided to place sharp crested weirs on the four sides of the pool and compare the rate of wave subsidence when some water was continually spilling over the weirs with the case of a pool with vertical sides and no gutters. Tests showed the range of wave height to be approximately one centimeter. Since accurate readings could be made to one one-hundredth of a centimeter, it was considered that a study of the effect of gutter design was entirely practicable.

However, it was soon found that, due to the warping of the wooden weirs and of the pool itself, it was a difficult task to keep the weirs at a constant level. Furthermore, no satisfactory, simple method could be found of duplicating gutter sections to scale, so that uniformity and constant level of gutter lip could be assured. Therefore, it seemed best to leave the study of gutter sections until some more satisfactory method of approach could be evolved. In this report data are given for the case in which overflow gutters are used, and for the case in which the water surface is confined by smooth, vertical walls. It is believed that these are the limiting cases, and that other types of gutter design will give rates of wave subsidence which will lie between those of these two limits.

The next step was to study the effect of longitudinal pool section on the waves; for while coaches all agree that some sections are better than others, they do not agree as to what type of section is preferable. By placing various false bottoms in the pool, very satisfactory and interesting results were obtained.

During swimming meets, cork floats about 6" in diameter are closely strung on lines which are stretched between the ends of the pool, on the surface of the water, so as to mark the lanes. It is generally believed that these lane markers have a beneficial effect on the quietness of the pool, and they are usually hung so as to float loosely upon the water. Simulating three lane markers in a pool, by placing cedar floats on a string, the rate of wave subsidence was studied for a given pool section without markers, and with the markers stretched tightly between the ends.

As an incidental study, a comparison of wave subsidence at the ends and side of each of two sections was made.

In addition to the studies described above, some definite information was desired concerning the mixing of incoming fresh water. The circulation system of a typical swimming pool was duplicated in the model, and brief tests on mixing were made by injecting dye into the incoming water and observing its manner of dispersion throughout the pool. This seemed a rather obvious method of approach, and gave information which may be of value.

2. Description of Apparatus.

(a) The Model Pool.

The model pool was designed to be a 1:8 scale model of a swimming pool 82 feet long, 50 feet wide, and 13 feet maximum depth. As constructed, it consisted of a box of inside dimensions 75 inches by 123 inches by 14 inches, built of sized 2" redwood planking. The joints between the redwood planks were splined, and calked with calking twist and white lead in order to obtain watertight construction. The box was supported upon 2x4 joists spaced at 18", which in turn rested upon three 3" I-beams, each of which were placed on 4" x 6" concrete posts, 17" above the floor, and fixed to the floor by tamp-in connections which extended through the posts to the I-beams. The depth of the pool was increased to the desired 20" by placing temporary 6" x $\frac{3}{4}$" oak boards, flush with the inside edge of the pool, on top of the permanent construction. These boards were beveled at a 45^{0} angle to a straight, sharp edge along one edge, and placed to form a continuous sharp-crested weir as the upper boundary of the pool.

Figure 1. The model pool.

The different sections to be studied were duplicated by inserting various false bottoms into the rectangular pool. These false bottoms were constructed of braced $\frac{1}{2}$" flooring, covered with light gage galvanized iron sheeting.

(b.) The Supply and Waste.

At the bottom of one end of the pool, about 10" from the end, two outlet valves were placed at the third points of the width. At the opposite, or shallow, end a one-inch header pipe was placed slightly above and beyond and parallel to the weir. Water was brought to the header through a hose connection to a water tap, and was delivered to the pool through three $\frac{1}{2}$" nipple and elbow connections which passed through the end weir at points three inches below the crest. One of these entrance points was at the center

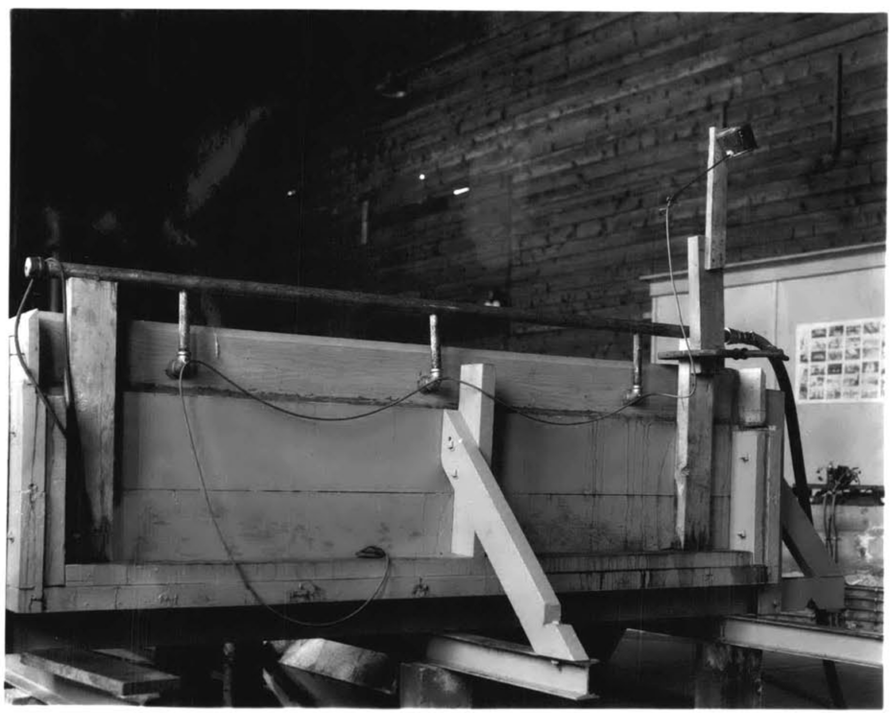


Figure 2. The inlet system.

of the end weir, the other two were placed 12" from the sides. Dye was injected into the stream through 1/32" I.D. brass tubing projecting through the back of the ½" elbows. A rubber tube connected the brass tubes with an elevated dye reservoir. Dye was injected at will by opening a pincer clamp on the rubber tube. The amount of water entering the pool was controlled at the water tap.

(c.) The Gage (For Reading Wave Height).

Wave height readings were made with a vernier point gage graduated in centimeters and reading directly to the nearest 0.01 cm. Readings were made in three places: at the center of each end, and at a point on the side of the pool one third of the pool length from the shallow end. All readings were made at points 6 inches distant in a normal direction out from the crest of the weir.

(d.) Method of Generating Waves.

As previously explained, the waves were generated by rotating a 12" board, which was immersed 3" throughout its length, through an angle of 90° about one end as an axis, in one corner of the pool in one second's time.

PART IV

TEST PROCEDURE

1. Preliminary Tests

The first tests on waves were made to determine the range of values, and the expected consistency of these values.

A small, smooth sliver of wood about two inches long was graduated in millimeters and attached to the side of the pool at the water level. A standard wave was generated by the rotation of a 12" board in one corner of the pool, as explained in the last section, and a stop watch started at the same instant. Twelve observations were made of the time for the maximum wave to die out until it was exactly 1.0 mm. above the mean water surface. The observed times ranged from 240 seconds to 260 seconds. Similar tests were made with water flowing over the weirs, and the time until the final wave 1.0 mm. high was found to vary from 90 seconds to 110 seconds. Considering the roughness of the gage, these results show good consistency; and the difference in reading between the two cases indicated that the method of approach was sound.

The point gage was, therefore, installed.

It now became desirable to determine more accurately the consistency to be expected in the generation of the "standard" wave. The point gage was set 1.0 mm. above mean water level, and the time from the start of the disturbance until the last wave touched the gage tip was noted. These observed times checked the above values almost exactly, and the method of wave generation was considered satisfactory.

During these preliminary tests it was found that trouble was to be expected in keeping the weir crests at the same elevation. To determine what effect the warping of the weirs might have, one of the end weirs was lowered ½ inch, so that water went over one end only, and the wave height-time observations were compared with a curve made from similar observations when water was passing over all the weirs at once. There was no perceptible difference. The same was true when water passed over one side only. Nevertheless, during all of the following tests care was taken to keep the weir crests at the proper elevation.

2. Tests on Wave Height.

These tests were made to determine data for defining curves of maximum wave height plotted against time for various conditions. For the case when the water surface was below the weirs the tests were complicated by a considerable amount of leakage at one of the seams of the wooden box.

Procedure:

(a) Determine the gage reading of the quiet water surface, and:

(b) Immediately generate the "standard" wave while starting the stop watch. Assume no drop in water level between steps (a) and (b).

(c) Set the gage so that it is touching the tops of the highest wave. Note the elapsed time in seconds each time a wave touches the gage, recording the last time that the gage is touched, together with the gage reading. When it is apparent that no more waves will touch the point, lower the gage and obtain another observation.

(d) When the water is quiet enough; obtain a gage reading of the mean water surface, noting the time.

(e) When the water surface is calm, repeat the above procedure, steps (a) through (d).

(f) After several sets of observations have been made, complete the wave height-time tabulation and make a rough plot of the curve. Then proceed with the test, setting the gage to obtain points to check questionable data, or to more fully define the curve.

3. Tests on Mixing of Incoming Water.

These tests were entirely of a visual, non-mathematical type. The inlet tap was adjusted to give the desired rate of flow, and the outlet valves were similarly adjusted. The rates of flow were determined by measuring the volume of water delivered to a calibrated container in a known time.

When steady conditions were obtained, the observer stood in an elevated position and opened the dye clamp as he started a stop watch. The dye was allowed to flow for 15 seconds, then was stopped. At regular intervals the observer made sketches of the dye pattern, noting the time. These sketches were used only for purposes of comparison.

4. Computations and Curves.

The only computations were those involved in completing the tabulation of wave height as ordinates vs. time as abscissae. Knowing the gage reading of the water surface before and after a test of known duration, the relative elevation at the intermediate recorded times was determined by interpolation, assuming that the rate of loss of water was constant. The difference between these values and the recorded gage readings of maximum wave height gave the height in centimeters of that maximum wave, for the given time, above the mean water surface.

Since the point gage is left at a constant elevation so that the time of the last wave of that height may be found, it is evident that the resulting wave height-time curve is an envelope enclosing an infinite number of possible points below it, and should have no points above it. The observed data for each case was plotted separately using wave height above mean water level as ordinates, and time in seconds from the instant of disturbance as abscissae. A curve was then drawn representing the most likely envelope, neglecting any peculiar points. During the first few seconds the true wave conditions were practically indeterminate. The curves were, therefore, drawn only between the limits within which the points indicated a definite curve. This curve was considered a measure of the quietness of a pool; the more quickly the sizw of waves decreased, the quieter the pool.

For purposes of comparison, certain groups of the curves were traced onto one sheet, omitting the plotted points.

No data were recorded concerning the mixing tests other than rough sketches showing the progressive diffusion of the dye.

5. Probable Precision of Results.

Excluding the personal or human chance of mistakes, the source of experimental error may be a combination of:

(a) Variation in the "standard" wave.

(b) Limitations of the measurement apparatus.

It is believed that the instrumental error was negligible in comparison with that due to variation in the disturbance causing the waves. However, most of the data were so consistent that it is believed that the plotted points are substantially accurate, and that excellent curves could be obtained if a great many points were determined for each. If any appreciable error is present in the position of the curves, it is undoubtedly due mainly to the lack of sufficient points to clearly define those curves. But without question all of the curves are sufficiently accurate for the purposes of comparison for which they were made.

PART V

RESULTS OF EXPERIMENTS

On the following pages are tabulated all of the experimental data of value to this report, and the curves derived from this data. (Plates 1 through 15).

Each section of the tabulation, as well as each plotted curve, is accompanied by a small sketch showing the section for which the data was obtained. The position of the gage is indicated by an arrow. The central figures are vertical dimensions; the lower figures are horizontal dimensions.

The abbreviation W.S. is used in placed of "water surface"

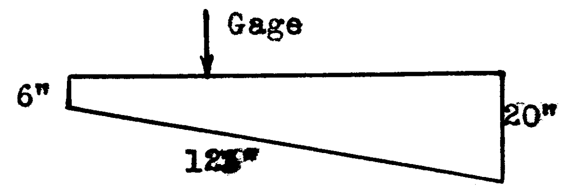
Plates 16 through 18 are typical sketches made while observing the mixing conditions of incoming water. Arrows indicate the positions of inlets and outlets in operation. Dark areas indicate the progressive mixing of the injected dye for the time shown, as measured from the instant when the dye clip was opened.

These figures are merely illustrative, or typical examples. To make complete and comprehensive sketches of each mixing test made would require a prohibitive amount of time; and it is doubtful whether they could properly be drawn so as to be capable of useful interpretation.

OBSERVED DATA

TESTS ON WAVE HEIGHT

A. Section:



1. Water elevation below the weirs.

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height Above Mean W.S. centimeters
0	34.45		
55	34.42	34.90	0.48
170	34.36	34.51	0.15
270	34.31	34.37	0.06
360	34.26		
0	34.23		
25	34.22	34.95	0.73
115	34.18	34.48	0.30
190	34.14	34.26	0.12
270	34.10	34.15	0.05
360	34.06		
0	34.05		
22	34.04	35.25	1.21
70	34.01	34.50	0.49
130	33.98	34.25	0.27
200	33.94	34.05	0.11
300	33.88	33.96	0.08
360	33.85		
0	33.84		
40	33.82	34.60	0.78
185	33.74	33.92	0.18
250	33.70	33.79	0.09
360	33.64		
0	34.95		
80	34.87	35.27	0.40
210	34.83	34.93	0.10
300	34.78	34.85	0.07
360	34.75		

OBSERVED DATA

TESTS ON WAVE HEIGHT

A. 1. (continued)

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height Above Mean W.S. centimeters
0	35.10		
80	35.02	35.47	0.45
165	34.93	35.14	0.21
250	34.85	34.96	0.11
300	34.80		
0	34.72		
4	34.72	36.00	1.28
130	34.65	34.90	0.25
215	34.60	34.75	0.15
310	34.55	34.62	0.07
360	34.52		
0	35.07		
35	35.03	35.46	0.43
200	34.82		
0	34.75		
35	34.71	35.35	0.64
130	34.62	34.85	0.23
255	34.49	34.58	0.09
300	34.45		
0	33.80		
145	33.65	33.90	0.25
260	33.54	33.62	0.08
300	33.50		
0	33.33		
95	33.23	33.62	0.39
200	33.14	33.30	0.16
340	33.03		
0	34.75		
110	34.64	34.98	0.34
280	34.47	34.56	0.09
300	34.45		

OBSERVED DATA

TESTS ON WAVE HEIGHT

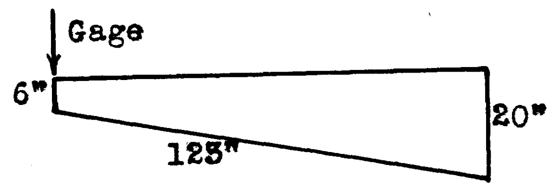
A. 2. Water going over the weirs on four sides.

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0			
75	35.88	35.95	0.07
120	"	35.88	0.00
18	"	36.10	0.22
73	"	35.96	0.08
120	"	35.88	0.00
14	"	36.15	0.27
100	"	35.90	0.02
25	"	36.10	0.22
85	"	35.94	0.06
10	"	36.20	0.32
75	"	35.94	0.06
30	35.84	36.00	0.16
38	"	36.00	0.16
33	35.79	35.99	0.20
30	"	35.98	0.19
14	"	36.04	0.25
100	"	35.84	0.05
60	"	35.92	0.13
16	"	36,04	0.25
45	"	35.94	0.15
53	"	35.92	0.13
63	"	35.89	0.10

OBSERVED DATA

TESTS ON WAVE HEIGHT

B. Section:



1. Water elevation below the weirs.

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	34.09		
100	33.99	34.14	0.15
0	33.60		
48	33.55	34.20	0.65
345	33.25	33.32	0.07
400	33.20		
0	32.92		
65	32.85	33.37	0.52
110	32.81	33.06	0.25
210	32.71	32.79	0.08
260	32.66	32.73	0.07
400	32.52		
0	33.82		
35	33.79	34.32	0.53
100	33.74	33.95	0.21
190	33.67	33.75	0.08
270	33.59	33.65	0.06
360	33.51		
0	33.31		
50	33.26	33.69	0.43
140	33.17	33.37	0.20
240	33.07	33.18	0.11
300	33.02		
0	32.92		
22	32.90	33.72	0.82
72	32.85	33.22	0.37
195	32.72	32.88	0.16
300	32.63	32.73	0.10

OBSERVED DATA

TESTS ON WAVE HEIGHT

B. 1. (cont.)

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	32.46		
14	32.45	33.23	0.78
90	32.37	32.70	0.33
200	32.26	32.41	0.15
280	32.18	32.28	0.10
300	32.16		
0	31.83		
75	31.75	32.24	0.49
300	31.53		
0	34.22		
30	34.19	34.75	0.56
165	34.05	34.20	0.15
230	33.99	34.09	0.10
300	33.92		
0	33.30		
33	33.27	33.98	0.71
105	33.22	33.53	0.31
195	33.14	33.30	0.16
285	33.07	33.18	0.11
300	33.06		
0	32.64		
45	32.60	33.15	0.55
225	32.46	32.55	0.09
300	32.40		
0	32.25		
75	32.19	32.56	0.37
165	32.12	32.25	0.13
250	32.05		
0	31.92		
120	31.82	32.06	0.24
180	31.77	31.93	0.16
240	31.72	31.83	0.11
300	31.68		

OBSERVED DATA

TESTS ON WAVE HEIGHT

B. 1. (cont.)

Time, Seconds	Mean W.S. Gage Reading centimeters	Maximum Wave Gage Reading centimeters	Maximum Wave Height above Mean W.S. centimeters
0	34.07		
40	33.04	33.73	0.70
100	33.97	34.31	0.28
175	33.90	34.06	0.16
280	33.79	33.89	0.10
300	33.75		
0	33.85		
55	33.79	34.39	0.60
180	33.66	33.85	0.19
220	33.62	33.74	0.12
300	33.53		
0	33.50		
70	33.43	32.82	0.39
120	33.38	33.61	0.23
210	33.29	33.43	0.14
280	33.22	33.30	0.08
300	33.19		
0	33.10		
30	33.07	33.82	0.75
115	32.98	33.22	0.24
190	32.91	33.07	0.16
250	32.85	32.95	0.10
330	32.77	32.85	0.08
400	32.68		
0	32.42		
58	32.36	32.78	0.42
155	32.26	32.43	0.17
260	32.16	32.26	0.10
300	32.10		
0	32.00		
90	31.91	32.15	0.24
200	31.80		

OBSERVED DATA

TESTS ON WAVE HEIGHT

B. 1. (cont.)

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	31.72		
60	31.66	32.22	0.56
130	31.59	31.80	0.21
225	31.49	31.60	0.11
290	31.43	31.53	0.10
300	31.42		
0	32.56		
26	32.53	33.33	0.80
95	32.46	32.76	0.30
240	32.32	32.41	0.09
300	32.26		

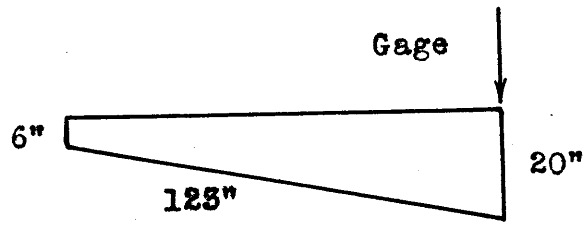
B. 2. Water going over the weirs on four sides.

0	35.10		
50	"	35.28	0.18
17	"	35.35	0.25
10	"	35.40	0.30
85	"	35.20	0.10
40	"	35.30	0.20
60	"	35.25	0.15
120	"	35.10	0.00
19	"	35.40	0.30
25	"	35.35	0.25
40	"	35.30	0.20
60	"	35.25	0.15
80	"	35.20	0.10
100	"	35.15	0.05
31	"	35.32	0.22
70	"	35.22	0.12
90	"	35.17	0.07

OBSERVED DATA

TESTS ON WAVE HEIGHT

C. Section:



1. Water surface below the weirs.

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	29.76		
45	29.71	30.36	0.65
140	29.62	29.95	0.33
210	29.55	29.71	0.16
300	29.47	29.58	0.11
300	29.46		
0	29.23		
35	29.19	30.02	0.83
105	29.12	29.51	0.39
185	29.04	29.21	0.17
270	28.96	29.08	0.12
300	28.93		
0	29.19		
70	29.12	29.65	0.53
125	29.06	29.44	0.38
205	28.99	29.14	0.15
300	28.89		
0	29.54		
48	29.49	30.24	0.75
110	29.43	29.81	0.38
230	29.31	29.46	0.15
330	29.21	29.31	0.10
400	29.14		
0	29.06		
50	29.01	29.63	0.62
160	28.90	29.14	0.24
260	28.80	28.93	0.13
300	28.76		

OBSERVED DATA

TESTS ON WAVE HEIGHT

C. 1. (cont.)

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	29.84		
85	29.75	30.21	0.46
160	29.68	29.93	0.25
250	29.59	29.72	0.13
300	29.54		
0	29.36		
45	29.31	30.01	0.70
125	29.23	29.58	0.35
190	29.17	29.34	0.17
260	29.10	29.22	0.12
300	29.06		
0	28.98		
75	28.90	29.40	0.50
140	28.84	29.15	0.31
245	28.73	28.87	0.14
330	28.65	28.73	0.08
400	28.58		

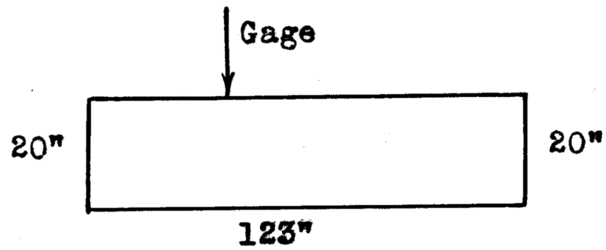
C. 2. Water going over the weirs on four sides.

0	31.15		
14	"	31.45	0.30
40	"	31.40	0.25
45	"	31.35	0.20
60	"	31.30	0.15
80	"	31.25	0.10
110	"	31.20	0.05
140	"	31.15	0.00
24	"	31.45	0.30
30	"	31.42	0.27
55	"	31.32	0.17
70	"	31.27	0.12
95	"	31.22	0.07

OBSERVED DATA

TESTS ON WAVE HEIGHT

D. Section:



1. Water surface below the weirs.

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	35.40		
7	35.40	36.47	1.07
58	35.37	35.80	0.43
400	35.20		
0	35.20		
48	35.18	35.87	0.69
130	35.13	35.54	0.41
225	35.09	35.29	0.20
355	35.02	35.14	0.12
400	35.00		
0	35.00		
48	34.98	35.75	0.77
140	34.93	35.35	0.42
180	34.92	35.12	0.20
360	34.84	34.95	0.11
400	34.82		
0	34.82		
21	34,81	35.66	0.85
90	34.72	35.26	0.54
280	34.68	34.84	0.16
400	34.63		
0	34.62		
30	34.60	35.47	0.87
100	34.57	35.08	0.51
180	35.53	34.79	0.26
290	34.47	34,63	0.16
400	34.42		

OBSERVED DATA

TESTS ON WAVE HEIGHT

D.1. (cont.)

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	34.40		
30	34.38	34.92	0.54
120	34.34	34.79	0.45
180	34.31	34.55	0.24
320	34.24	34.39	0.15
400	34.20		
0	35.38		
12	35.37	36.33	0.96
70	35.34	35.97	0.63
160	35.30	35.65	0.35
280	35.24	35.40	0.16
400	35.18		
0	35.18		
32	35.16	35.97	0.81
110	35.12	35.48	0.36
210	35.08	35.30	0.22
310	35.03	35.13	0.10
400	34.98		
0	34.96		
38	34.94	35.72	0.78
110	34.91	35.42	0.51
200	34.86	35.10	0.24
335	34.78	34.91	0.13
400	34.76		
0	34.76		
19	34.75	35.66	0.91
80	34.72	35.29	0.57
150	34.68	34.98	0.30
260	34.63	34.82	0.19
350	34.58	34.65	0.07
400	34.56		

OBSERVED DATA

TESTS ON WAVE HEIGHT

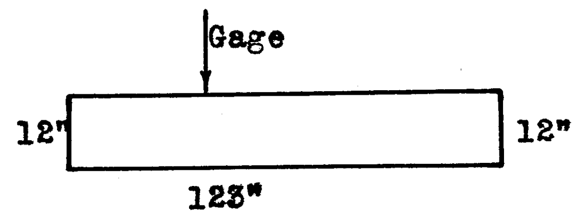
D. 2. Water going over the weirs on four sides.

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	36.25		
12	"	36.55	0.30
22	"	36.50	0.25
35	"	36.45	0.20
47	"	36.40	0.15
60	"	36.35	0.10
80	"	36.30	0.05
120	"	36.25	0.00
19	"	36.52	0.27
30	"	36.47	0.22
38	"	36.42	0.17
50	"	36.37	0.12
75	"	36.32	0.07
40	"	36.43	0.18

OBSERVED DATA

TESTS ON WAVE HEIGHT

E. Section:



1. Water surface below the weirs.

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	14.66		
82	14.65	15.57	0.92
230	14.64	15.10	0.46
370	14.62	14.93	0.31
445	14.62	14.85	0.23
500	14.61		
0	14.61		
34	14.61	15.81	1.20
140	14.60	15.26	0.66
280	14.58	15.00	0.42
400	14.57		
0	14.56		
70	14.55	15.53	0.98
100	14.55	15.26	0.71
310	14.53	14.88	0.35
400	14.53		
0	14.53		
50	14.53	15.59	1.06
100	14.52	15.26	0.74
190	14.51	15.05	0.54
270	14.51	14.91	0.40
380	14.50	14.81	0.31
400	14.50		

OBSERVED DATA

TESTS ON WAVE HEIGHT

E. 1. (cont.)

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	14.49		
70	14.48	15.42	0.94
165	14.48	15.07	0.59
210	14.47	14.95	0.48
300	14.47	14.82	0.35
400	14.46		

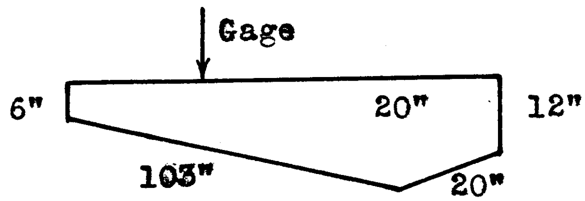
E. 2. Water going over the weirs on four sides.

0	36.35		
12	"	36.70	0.35
22	"	36.65	0.30
30	"	36.60	0.25
39	"	36.55	0.20
51	"	36.50	0.15
65	"	36.45	0.10
90	"	36.40	0.05
140	"	calm	----

OBSERVED DATA

TESTS ON WAVE HEIGHT

F. Section:



1. Water elevation below the weirs.

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	34.79		
48	34.78	35.36	0.58
155	34.76	34.96	0.20
250	34.74	34.82	0.08
300	34,73		
0	34.67		
13	34.67	35.75	1.08
120	34.65	34.97	0.32
210	34.63	34.75	0.12
290	34.61	34.69	0.08
300	34.61		
0	34.46		
33	34.46	35.30	0.84
205	34.42	34.55	0.13
310	34.40	34.45	0.05
320	34.40		
0	34.34		
90	34.33	34.81	0.48
200	34.30	34.41	0.11
300	34.28	34.33	0.05
300	34.28		
0	34.20		
33	34.20	34.89	0.69
95	34.18	34.57	0.39
160	34.15	34.29	0.14
300	34.14		

OBSERVED DATA

TESTS ON WAVE HEIGHT

F. 1. (cont.)

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	34.08		
25	34.08	34.98	0.90
130	34.05	34.34	0.29
250	34.03	34,17	0.14
300	34.02		
0	33.92		
60	33.91	34.43	0.52
180	33.89	34,04	0.15
300	33.86	33.92	0.06
300	33.86		
0	34.67		
40	34.66	35.27	0.61
110	34.65	34.99	0.34
200	34.63	34.77	0.14
300	34.61		
0	34.60		
80	34.59	35.01	0.42
220	34.56	34.67	0.11
320	34.54	34.60	0.06
350	34.53		
0	34.51		
48	34.50	35.07	0.56
140	34.48	34.74	0.26
260	34.46	34.53	0.07
300	34.45		

OBSERVED DATA

TESTS ON WAVE HEIGHT

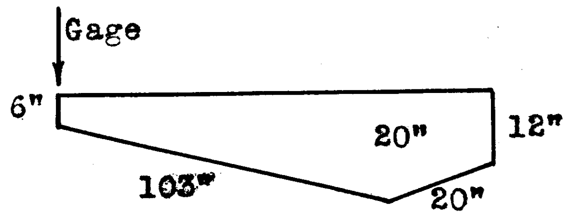
F. 2. Water going over the weirs on four sides.

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	36.07		
16	"	36.37	0.30
22	"	36.32	0.25
29	"	36.27	0.20
34	"	36.22	0.15
60	"	36.17	0.10
70	"	36.12	0.05
100	"	36.07	0.00
5	"	36.42	0.35
50	"	36.19	0.12
38	"	36.24	0.17
75	"	36.12	0.05

OBSERVED DATA

TESTS ON WAVE HEIGHT

G. Section:



1. Water surface below the weirs.

Time, Seconds	Mean W.S. Gage Reading centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	33.74		
7	33.74	34.85	1.11
115	33.72	33.96	0.24
220	33.70	33.79	0.09
300	33.68		
0	33.54		
10	33.54	34.41	0.87
25	33.54	34.31	0.77
120	33.52	33.73	0.21
195	33.50	33.66	0.16
300	33.48		
0	33.31		
150	33.28	33.45	0.17
240	33.26	33.36	0.10
300	33.25		
0	33.18		
25	33.18	33.75	0.57
65	33.17	33.55	0.38
180	33.14	33.26	0.12
225	33.14	33.21	0.07
300	33.12		
0	30.04		
50	30.03	33.46	0.43
95	30.02	33.31	0.29
200	30.00	33.10	0.10
300	29.98	33.03	0.05
300	29.98		

OBSERVED DATA

TESTS ON WAVE HEIGHT

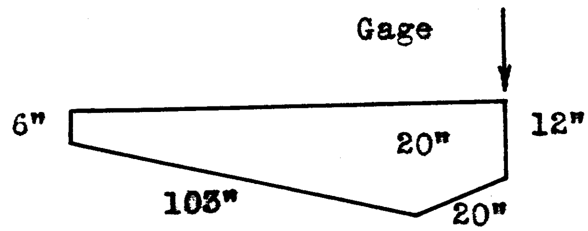
G. 1. (cont.)

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	33.67		
18	33.67	34,35	0.68
90	33.65	33.95	0.30
200	33.63	33.74	0.11
290	33.61	33.67	0.06
300	33.61		
0	33.54		
31	33.54	34.08	0.54
125	33.52	33.74	0.22
250	33.49	33.57	0.08
300	33.48		
0	33.41		
30	33.41	33.85	0.44
135	33.38	33.58	0.20
190	33.37	33.48	0.11
300	33.35	33.40	0.05
300	33.35		
0	33.29		
39	33.28	33.78	0.50
105	33.27	33.51	0.24
210	33.25	33.35	0.10
250	33.24		

OBSERVED DATA

TESTS ON WAVE HEIGHT

H. Section:



1. Water surface below the weirs.

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	31.09		
80	31.07	31.50	0.43
150	31.06	31.24	0.18
240	31.04	31.12	0.08
280	31.03	31.10	0.07
300	31.03		
0	30.94		
7	30.94	31.78	0.84
85	30.92	31.31	0.39
150	30.91	31.09	0.18
265	30.89	30.96	0.07
300	30.88		
0	30.76		
31	30.75	31.40	0.65
100	30.73	31.06	0.33
235	30.71	30.82	0.11
300	30.70		
0	30.58		
25	30.58	31.31	0.73
110	30.56	30.85	0.29
320	30.52	30.57	0.05
350	30.52		

OBSERVED DATA

TESTS ON WAVE HEIGHT

H. 1. (cont.)

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	30.45		
50	30.44	30.98	0.54
140	30.42	30.62	0.20
225	30.40	30.51	0.11
300	30.39		
0	30.31		
21	30.31	31.02	0.71
70	30.30	30.75	0.45
155	30.28	30.44	0.16
300	30.25	30.31	0.06
300	30.25		
0	30.10		
39	30.09	30.69	0.60
120	30.08	30.34	0.26
205	30.06	30.18	0.12
300	30.04		

OBSERVED DATA

TESTS ON WAVE HEIGHT

I. Section: Same as F, with three floating lane markers, loose.

1. Water surface below the weirs.

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	35.38		
12	35.38	36.24	0.86
95	35.36	35.69	0.33
150	35.35	35.47	0.12
205	35.34	35.42	0.08
270	35.32	35.34	0.02
300	35.32		
0	35.20		
21	35.20	35.81	0.61
100	35.18	35.45	0.27
185	35.17	35.24	0.07
240	35.15	35.17	0.02
270	35.15		
360	-----		0.00
0	35.33		
22	35.33	36.05	0.72
100	35.32	35.63	0.31
160	35.31	35.43	0.12
210	35.31	35.37	0.06
300	35.30		
0	35.25		
45	35.25	35.75	0.50
140	35.24	35.40	0.16
240	35.23	35.27	0.04
300	35.22		
0	35.20		
19	35.20	35.86	0.66
70	35.19	35.58	0.39
150	35.18	35.32	0.14
270	35.17	35.19	0.02
300	35.17		

OBSERVED DATA

TESTS ON WAVE HEIGHT

I. 1. (cont.)

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	35.09		
35	35.09	35.64	0.55
300	35.06		
0	35.05		
39	35.05	35.52	0.47
130	35.04	35.23	0.19
300	35.02		

I. 2. Water going over the weirs on four sides.

0	36.51		
8	"	36.86	0.35
17	"	36.81	0.30
22	"	36.76	0.25
33	"	36.71	0.20
39	"	36.63	0.12
49	"	36.61	0.10
55	"	36.56	0.05
75	"	36.53	0.02
70	"	36.53	0.02
90	"	calm	calm

OBSERVED DATA

TESTS ON WAVE HEIGHT

J. Section: Same as F, with three floating lane markers, tight

1. Water elevation below the weirs.

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	36.04		
6	36.04	36.75	0.71
75	36.03	36.20	0.17
165	36.02	36.10	0.08
200	36.02		
0	35.87		
12	35.87	36.46	0.59
40	35.87	36.09	0.22
125	35.86	35.93	0.07
200	35.85		
0	35.69		
30	35.69	36.18	0.49
90	35.68	35.86	0.18
145	35.68	35.75	0.07
210	35.67	35.72	0.05
300	35.66		quiet
0	35.55		
22	35,55	36.25	0.70
60	35.54	35.84	0.30
125	35.54	35.65	0.11
200	35.53	35.60	0.07
200	35.53		
300			quiet
0	35.45		
32	35.45	35.86	0.41
100	35.44	35.61	0.17
200	35.43	35.49	0.06
200	35.43		

OBSERVED DATA

TESTS ON WAVE HEIGHT

J. 1. (cont.)

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	35.36		
48	35.36	35.74	0.38
110	35.35	35.49	0.14
215	35.34	35.39	0.05
250	35.34		
0	35.25		
20	35.25	35.79	0.54
80	35.24	35.47	0.23
180	35.23	35.31	0.08
300	35.22		quiet

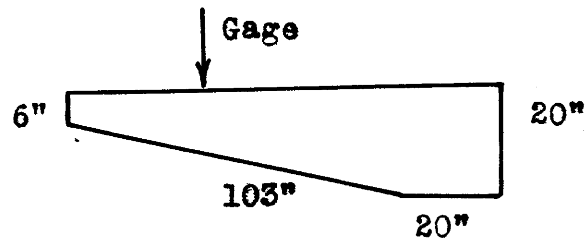
J. 2. Water going over the weirs on four sides.

0	36.46		
9	"	36.76	0.30
12	"	36.71	0.25
20	"	36.66	0.20
26	"	36.61	0.15
31	"	36.56	0.10
50	"	36.51	0.05
60	"		quiet
40	"	36.53	0.07

OBSERVED DATA

TESTS ON WAVE HEIGHT

K. Section:



1. Water surface below the weirs.

Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	35.66		
12	35.66	36.54	0.88
80	35.66	36.12	0.46
115	35.66	36.02	0.36
230	35.65	35.82	0.17
280	35.65	35.77	0.12
400	35.64		
0	35.53		
42	35.53	36.15	0.62
100	35.53	35.88	0.35
240	35.52	35.69	0.17
310	35.51	35.60	0.09
350	35.51		
0	35.45		
28	35.45	36.23	0.78
90	35.45	35.88	0.43
170	35.44	35.68	0.24
255	35.44	35.58	0.14
400	35.43		
0	35.38		
60	35.38	35.93	0.55
150	35.37	35.65	0.28
250	35.37	35.52	0.15
325	35.36	35.44	0.08
400	35.36		

OBSERVED DATA

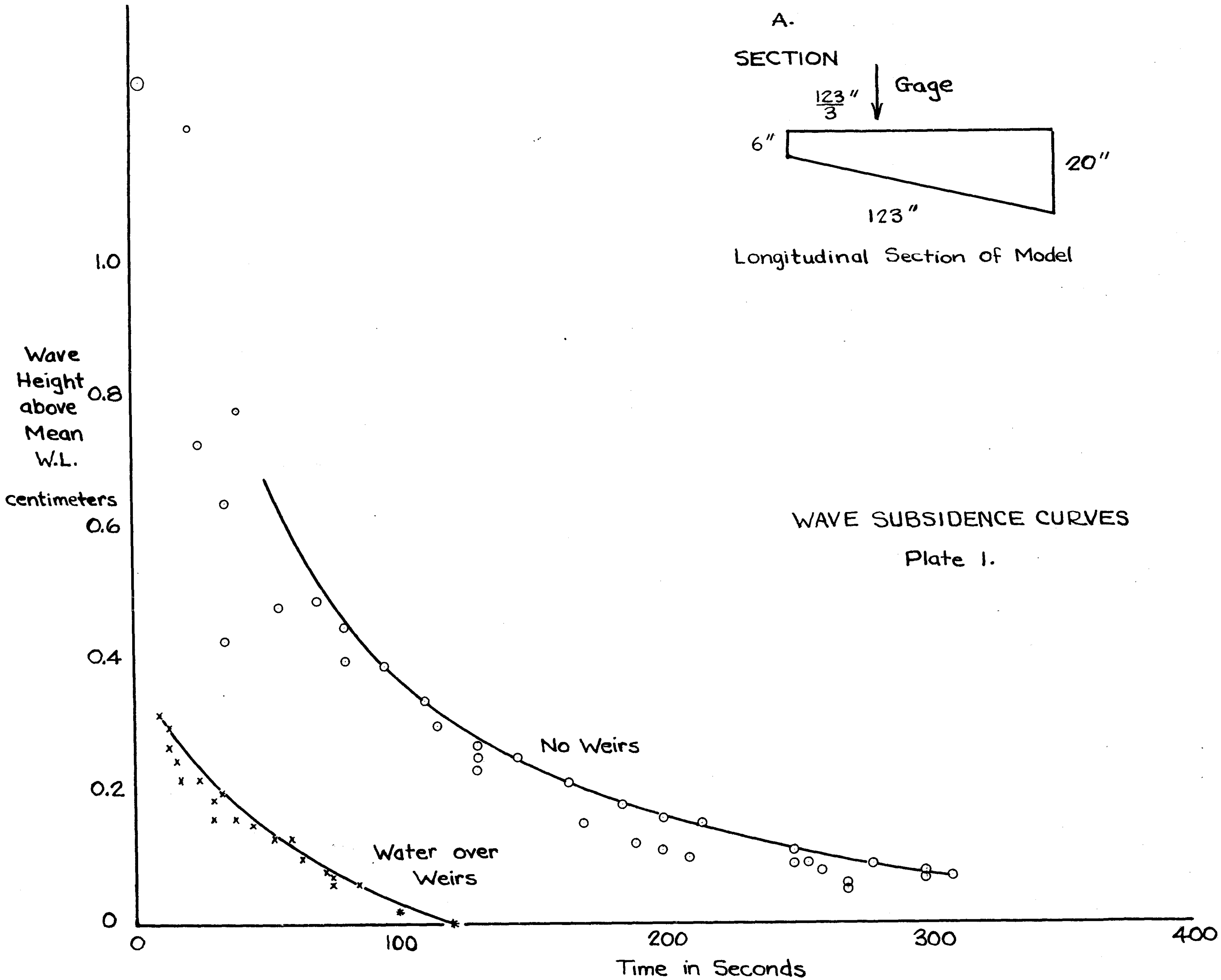
TESTS ON WAVE HEIGHT

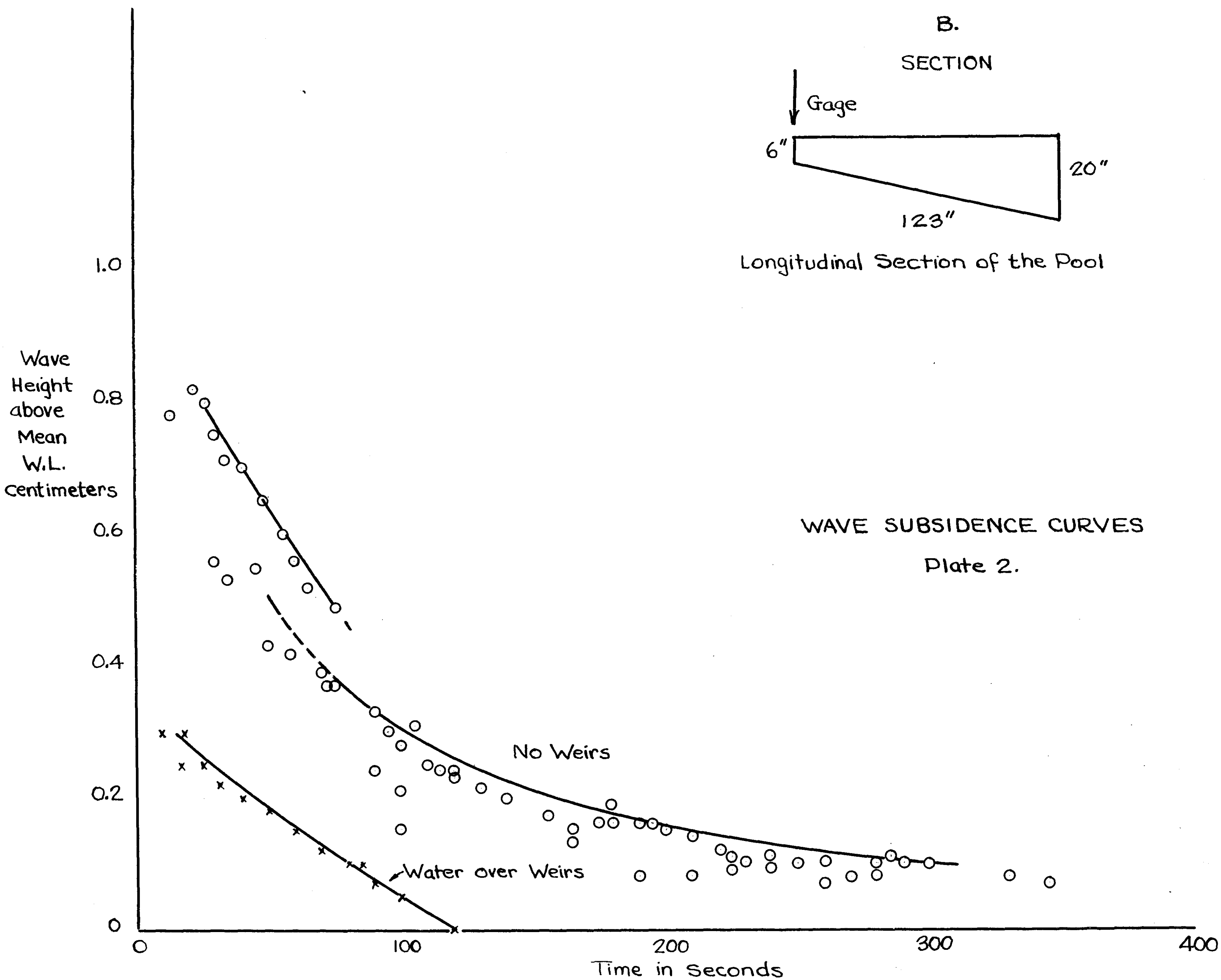
K. 1. (cont.)

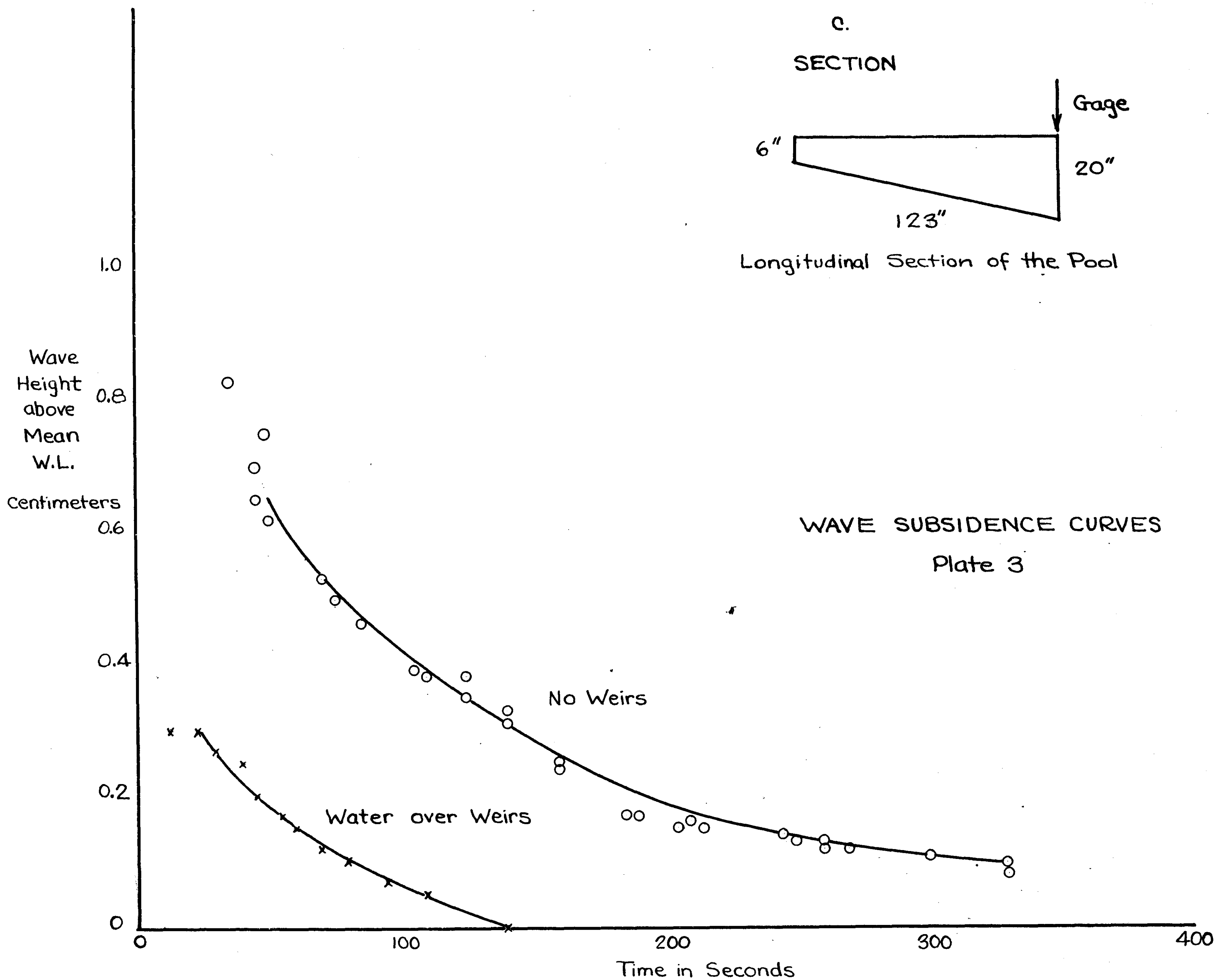
Time, Seconds	Mean W.S. Gage Reading, centimeters	Maximum Wave Gage Reading, centimeters	Maximum Wave Height above Mean W.S. centimeters
0	35.29		
21	35.29	36.05	0.76
95	35.29	35.70	0.41
150	35.28	35.55	0.27
270	35.27	35.39	0.12
400	35.27		
0	35.12		
35	35.12	35.81	0.69
130	35.12	35.44	0.32
245	35.11	35.37	0.16
350	35.10	35.16	0.06
400	35.10		

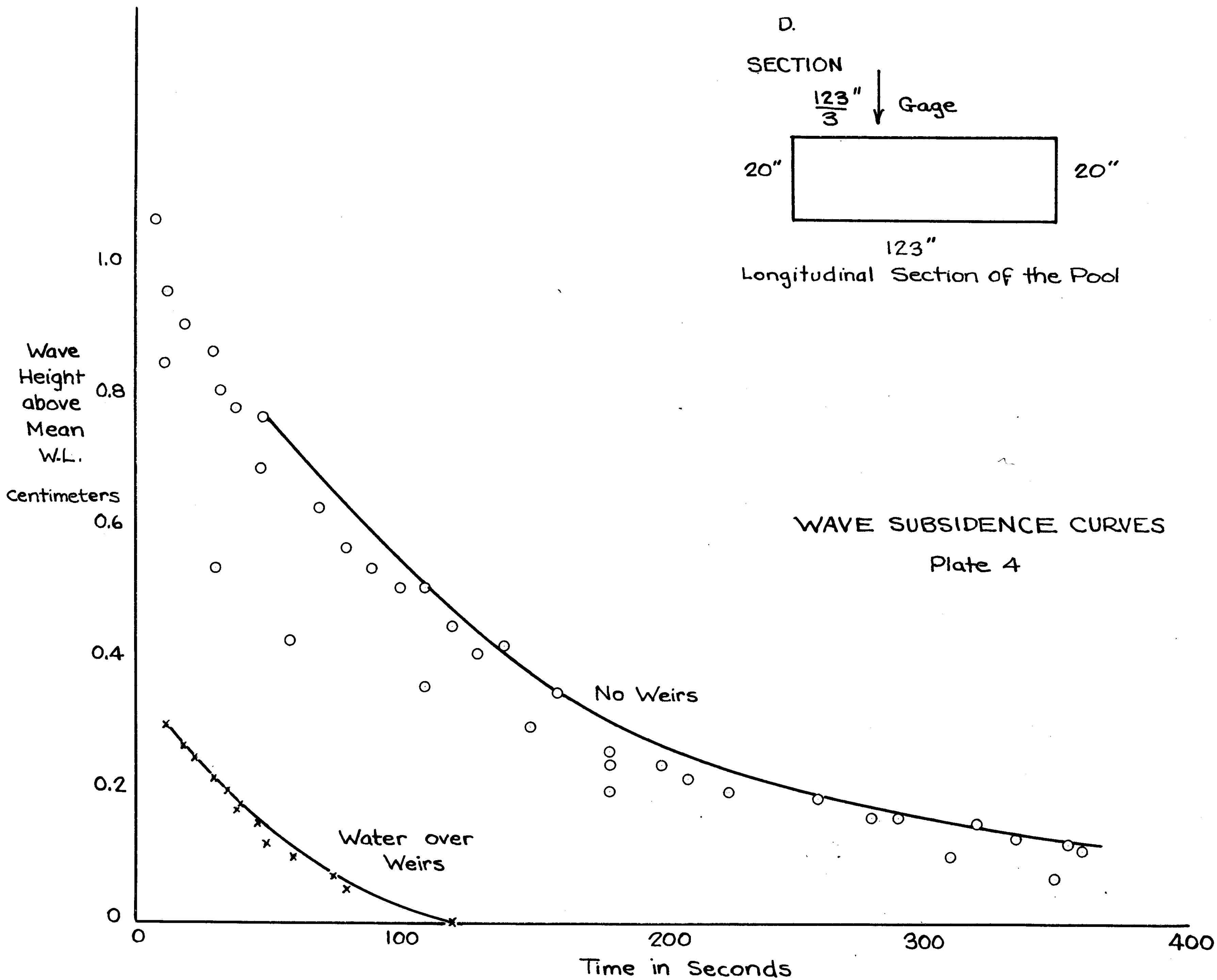
K. 2. Water going over the weirs on 4 sides.

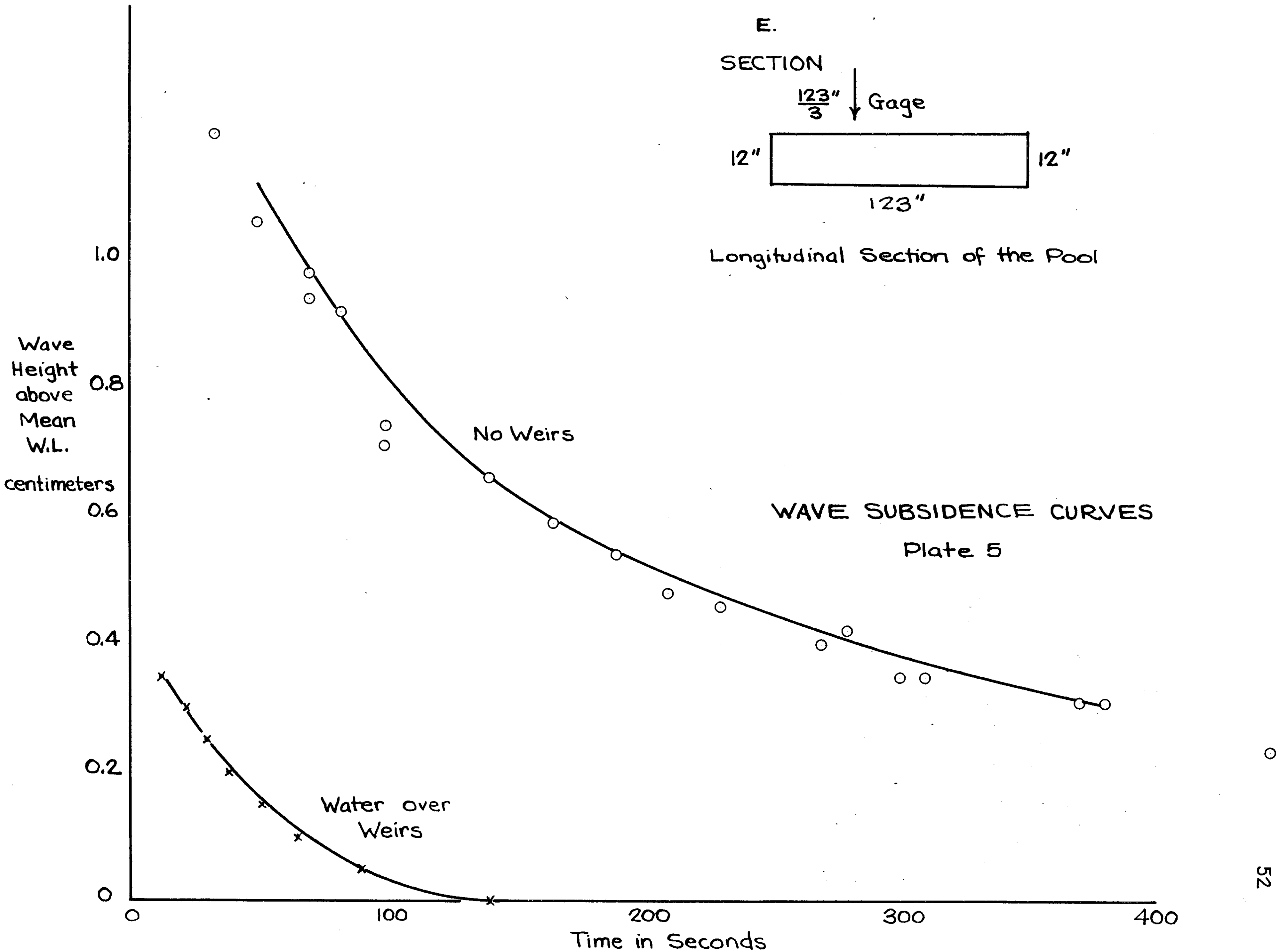
0	36.48		
12	"	36.83	0.35
18	"	36.78	0.30
23	"	36.73	0.25
32	"	36.68	0.20
37	"	36.63	0.15
58	"	36.58	0.10
62	"	36.53	0.05
100	"		quiet


A.
SECTION
Gage
123/3"
6"
20"
123"
Longitudinal Section of Model
WAVE SUBSIDENCE CURVES
Plate 1.
Wave Height above Mean W.L. centimeters
1.0
0.8
0.6
0.4
0.2
0
0
100
200
300
400
Time in Seconds
No Weirs
Water over Weirs

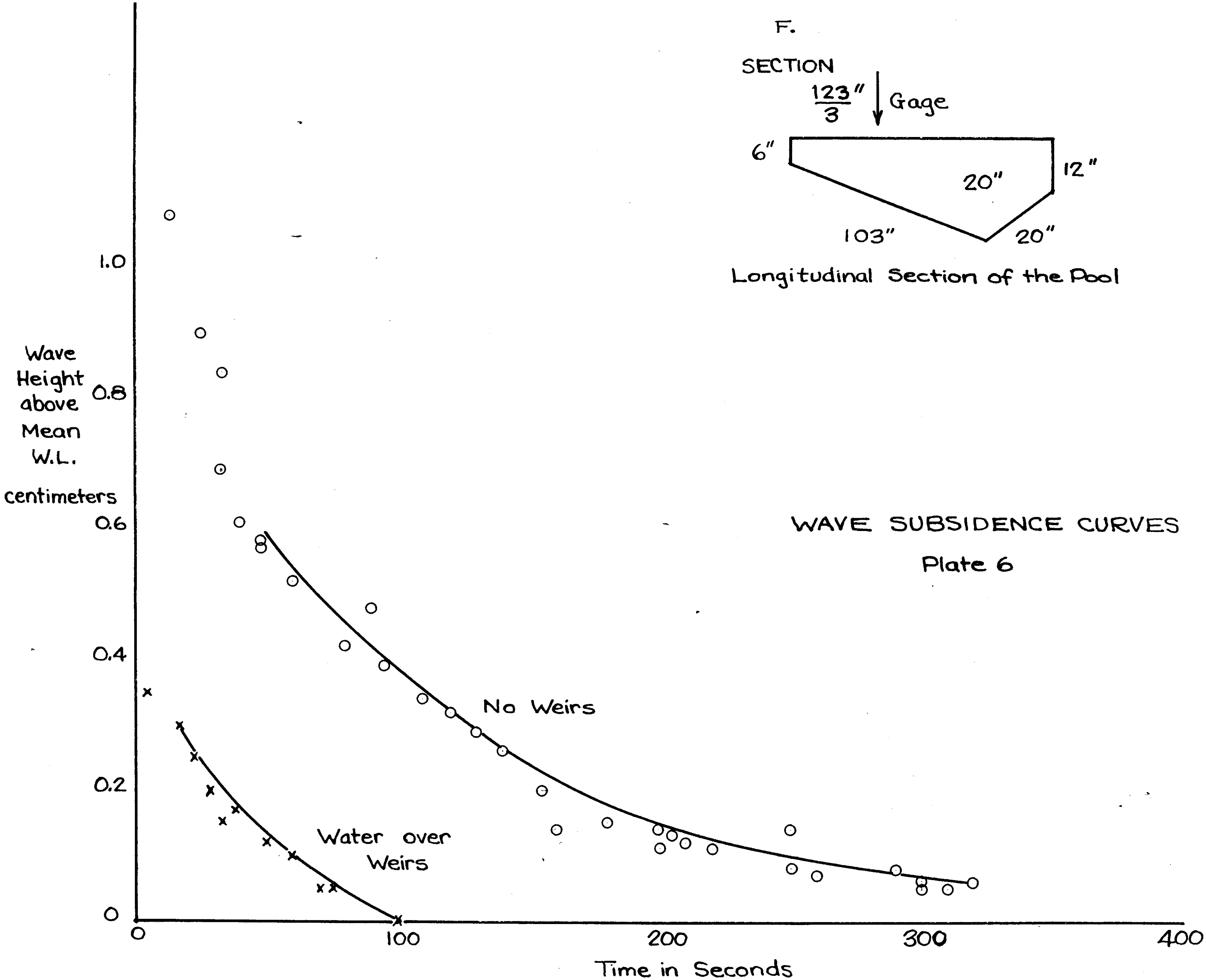

B.
SECTION
Gage
6"
20"
123"
Longitudinal Section of the Pool
WAVE SUBSIDENCE CURVES
Plate 2.
Wave Height above Mean W.L. centimeters
1.0
0.8
0.6
0.4
0.2
0
No Weirs
Water over Weirs
0
100
200
300
400
Time in Seconds


C.
SECTION
Gage
6"
20"
123"
Longitudinal Section of the Pool
WAVE SUBSIDENCE CURVES
Plate 3
Wave Height above Mean W.L.
Centimeters
1.0
0.8
0.6
0.4
0.2
0
No Weirs
Water over Weirs
0
100
200
300
400
Time in Seconds


D.
SECTION
$\frac{123}{3}$"
Gage
20"
20"
123"
Longitudinal Section of the Pool
WAVE SUBSIDENCE CURVES
Plate 4
Wave Height above Mean W.L.
Centimeters
1.0
0.8
0.6
0.4
0.2
0
No Weirs
Water over Weirs
0
100
200
300
400
Time in Seconds

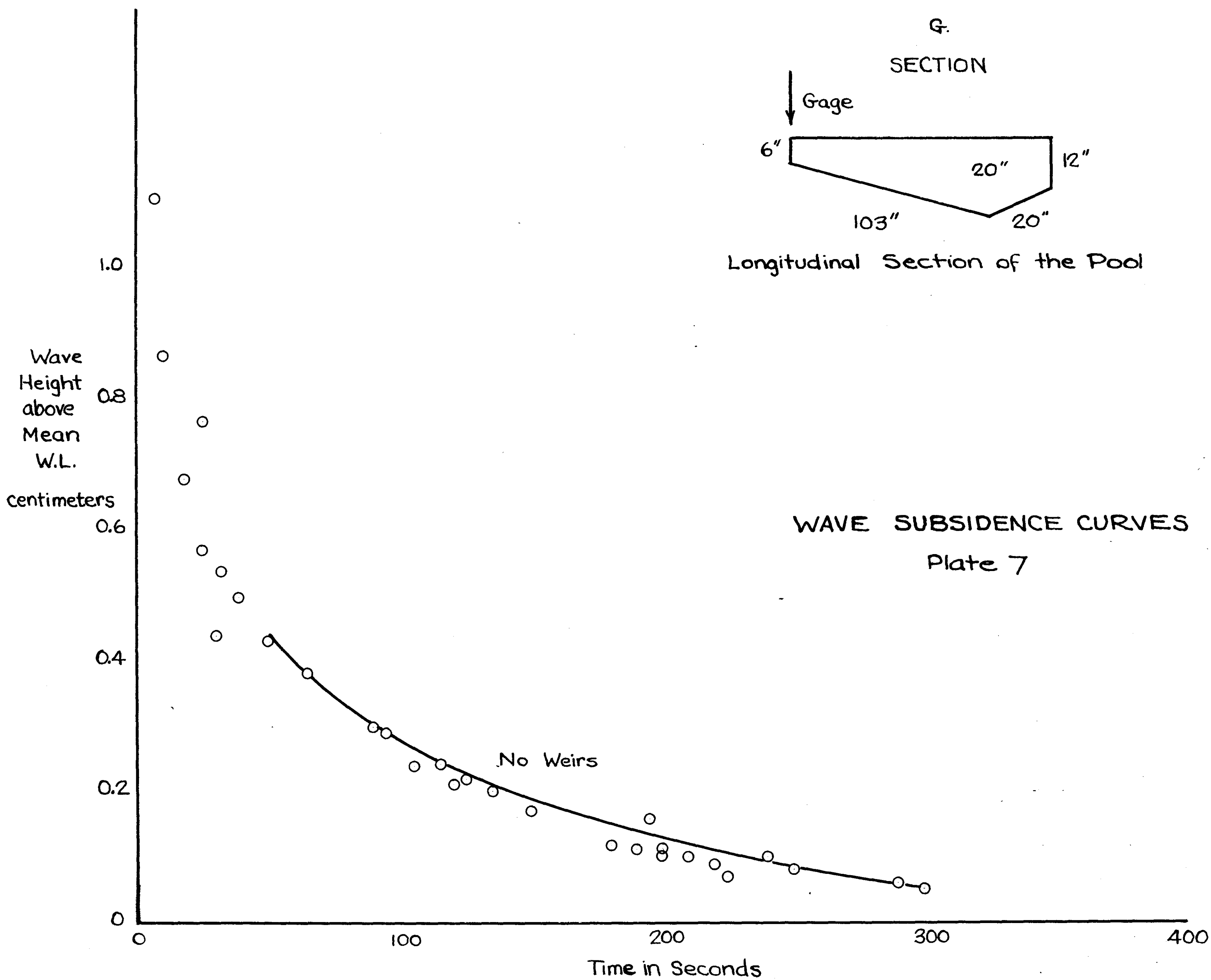


E.
SECTION
123"/3
Gage
12"
12"
123"
Longitudinal Section of the Pool
WAVE SUBSIDENCE CURVES
Plate 5
Wave Height above Mean W.L.
centimeters
1.0
0.8
0.6
0.4
0.2
0
No Weirs
Water over Weirs
0
100
200
300
400
Time in Seconds

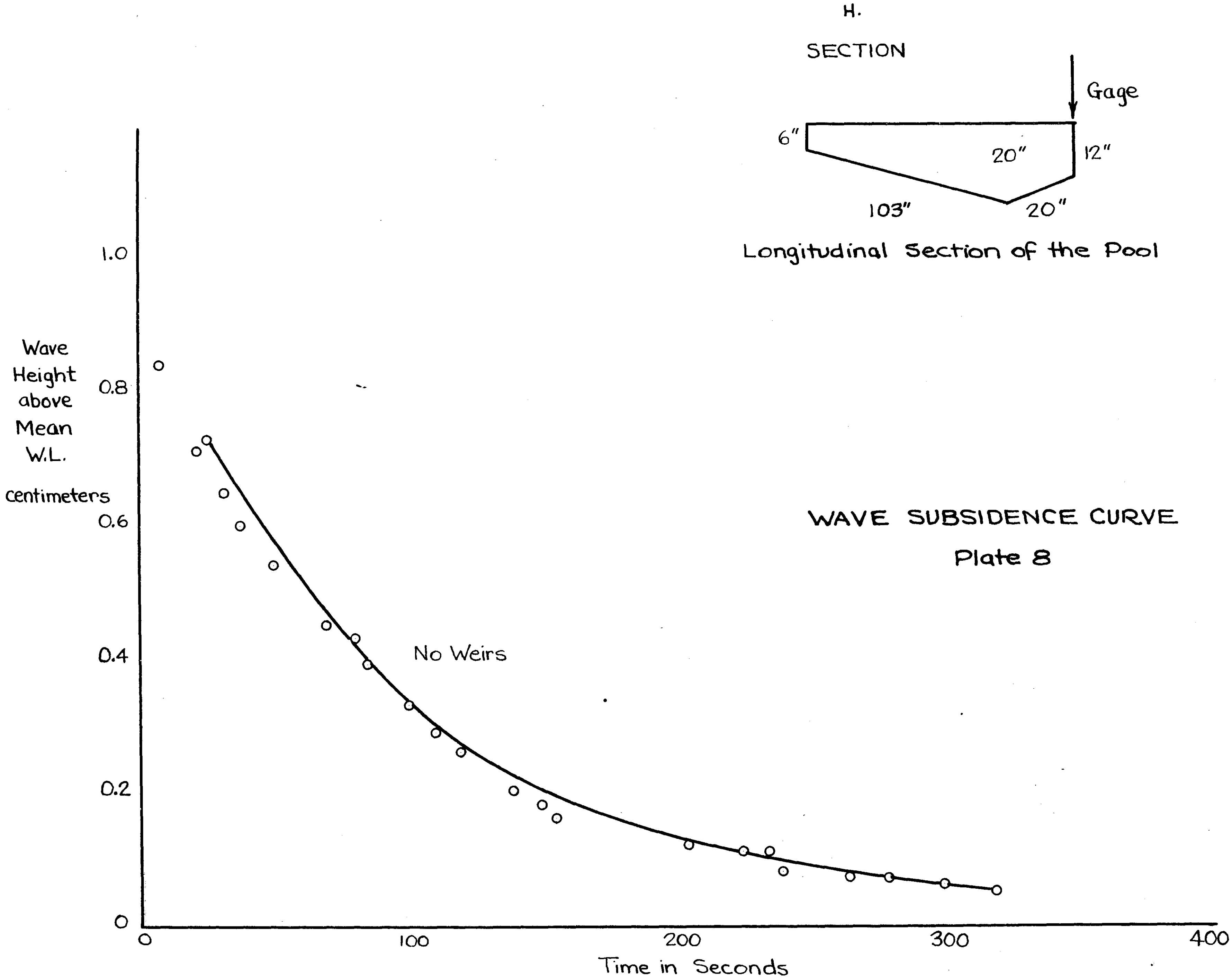


WAVE SUBSIDENCE CURVES

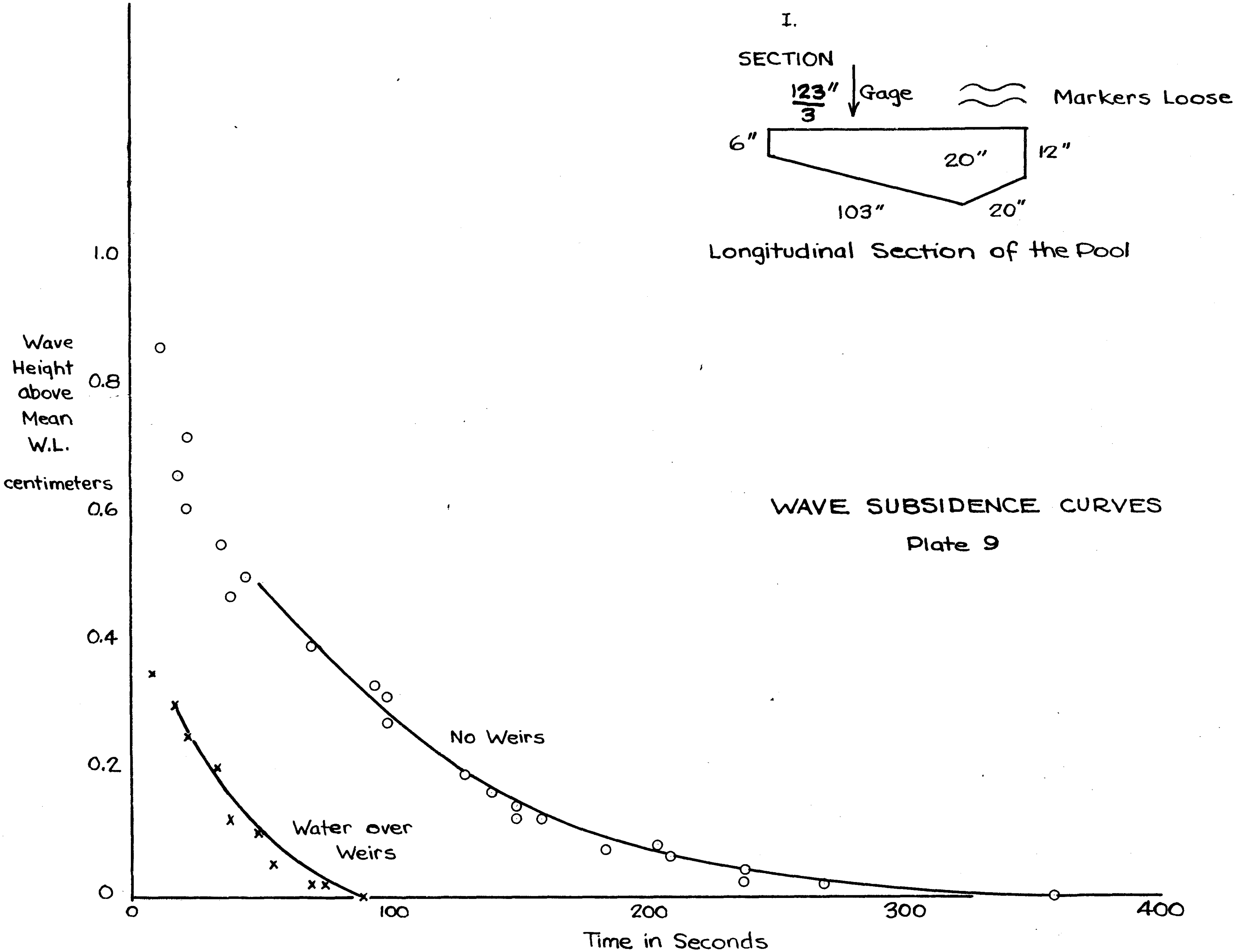
Plate 6



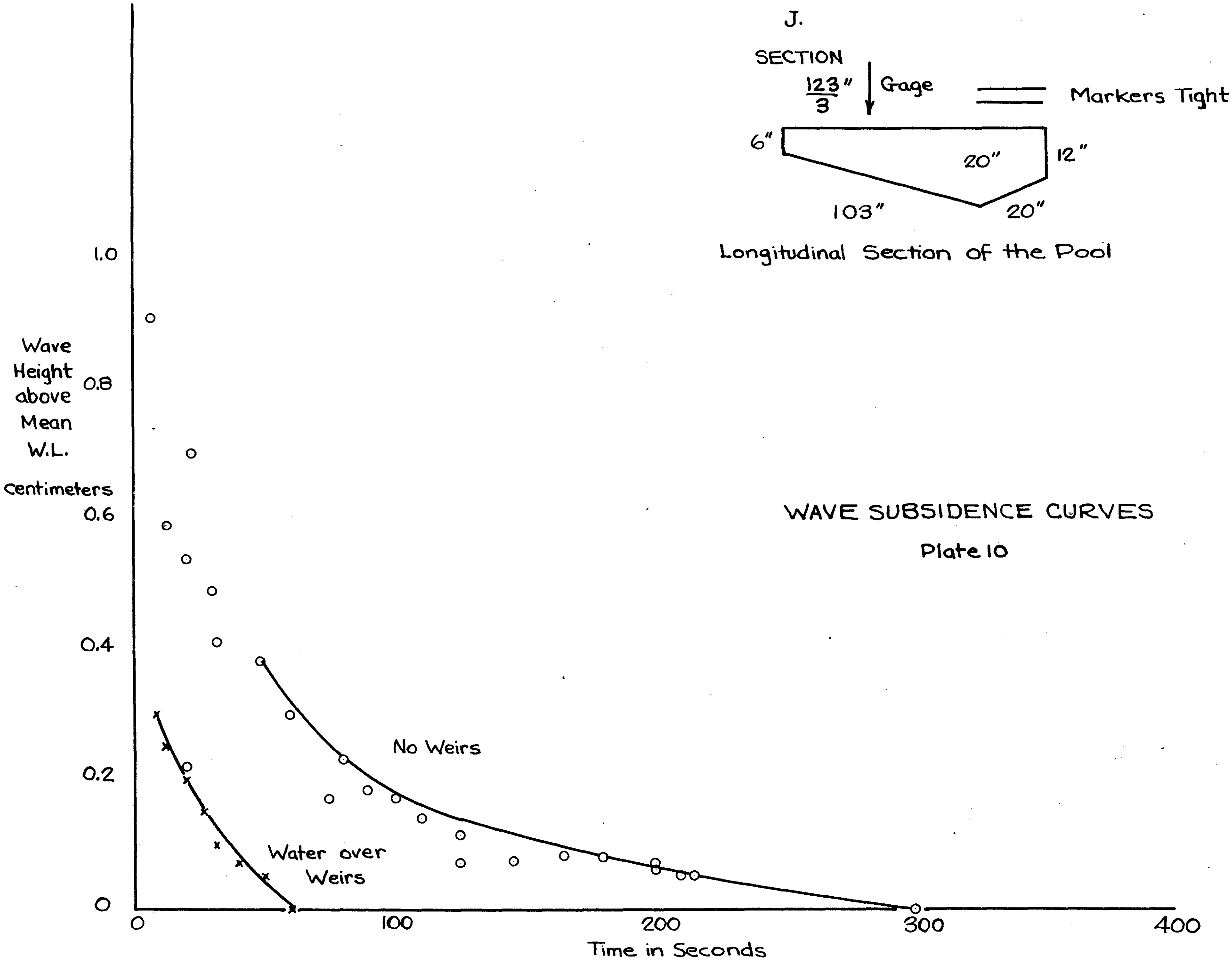
WAVE SUBSIDENCE CURVES
Plate 7

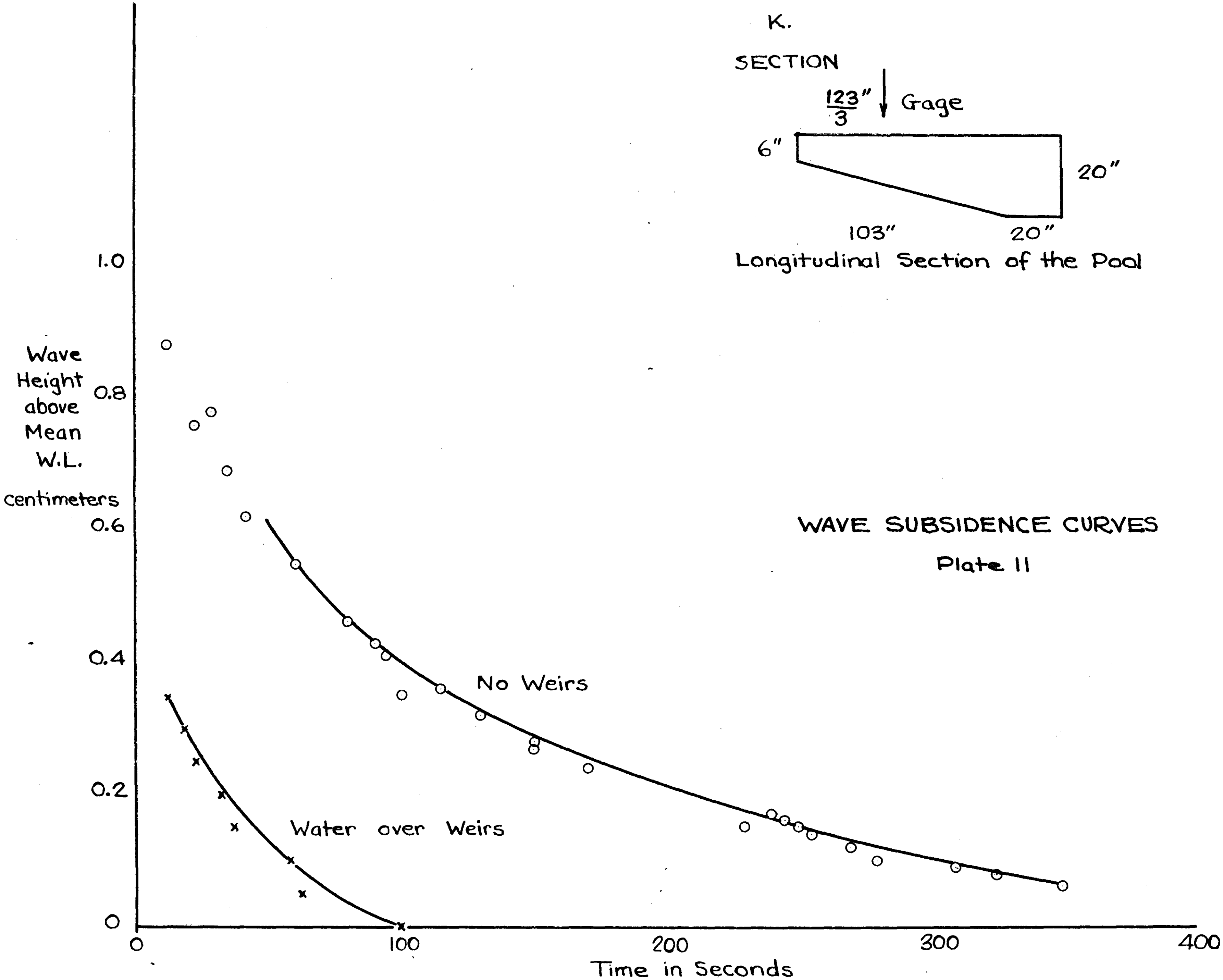


WAVE SUBSIDENCE CURVE
Plate 8



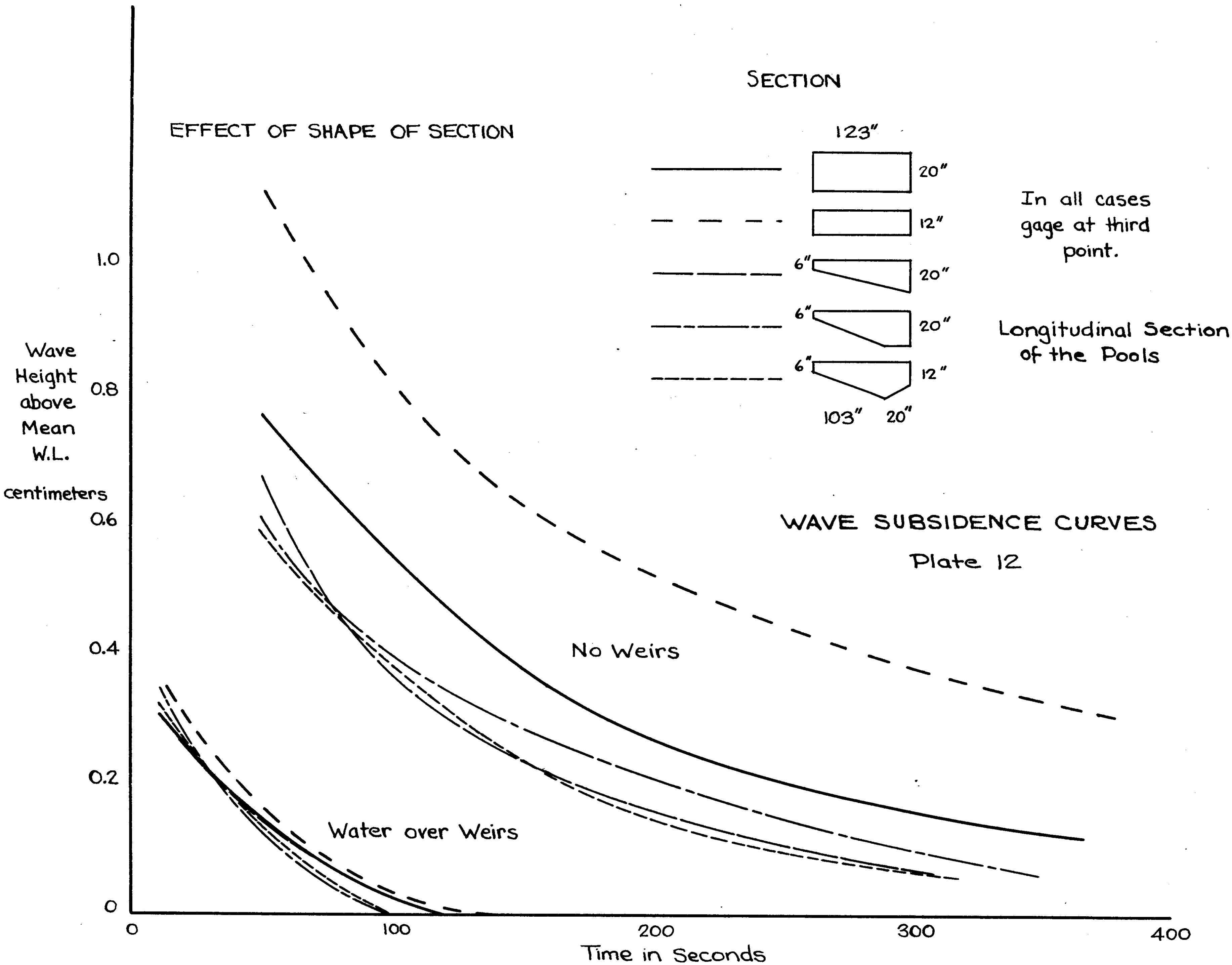
WAVE SUBSIDENCE CURVES
Plate 9


J.
SECTION
123"/3
Gage
Markers Tight
6"
20"
12"
103"
20"
Longitudinal Section of the Pool
WAVE SUBSIDENCE CURVES
Plate 10
Wave Height above Mean W.L. centimeters
1.0
0.8
0.6
0.4
0.2
0
No Weirs
Water over Weirs
0
100
200
300
400
Time in Seconds



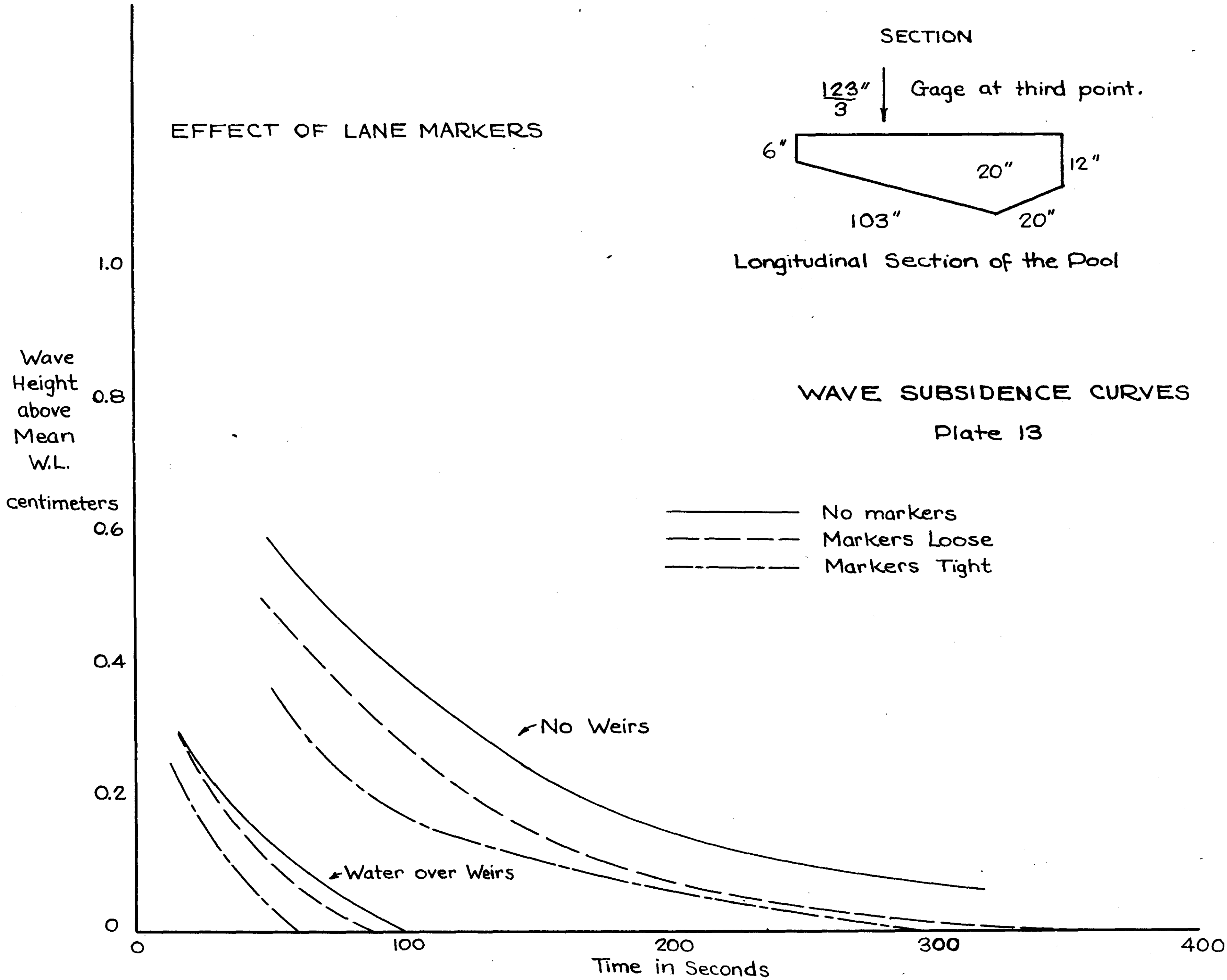
WAVE SUBSIDENCE CURVES

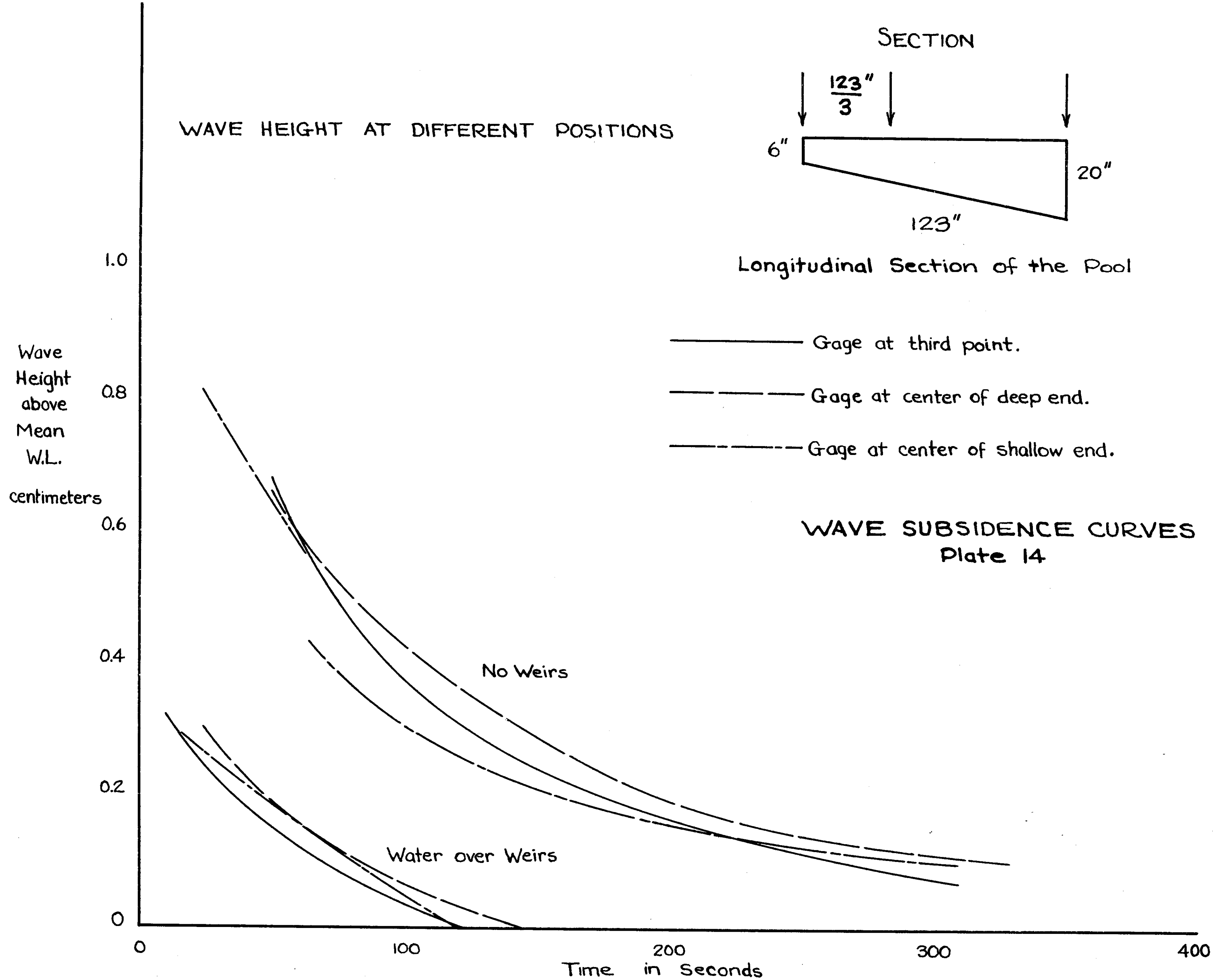
Plate II



WAVE SUBSIDENCE CURVES

Plate 12


EFFECT OF LANE MARKERS
SECTION
123″/3
Gage at third point.
6″
20″
12″
103″
20″
Longitudinal Section of the Pool
WAVE SUBSIDENCE CURVES
Plate 13
No markers
Markers Loose
Markers Tight
No Weirs
Water over Weirs
Wave Height above Mean W.L.
centimeters
1.0
0.8
0.6
0.4
0.2
0
0
100
200
300
400
Time in Seconds



WAVE SUBSIDENCE CURVES
Plate 14

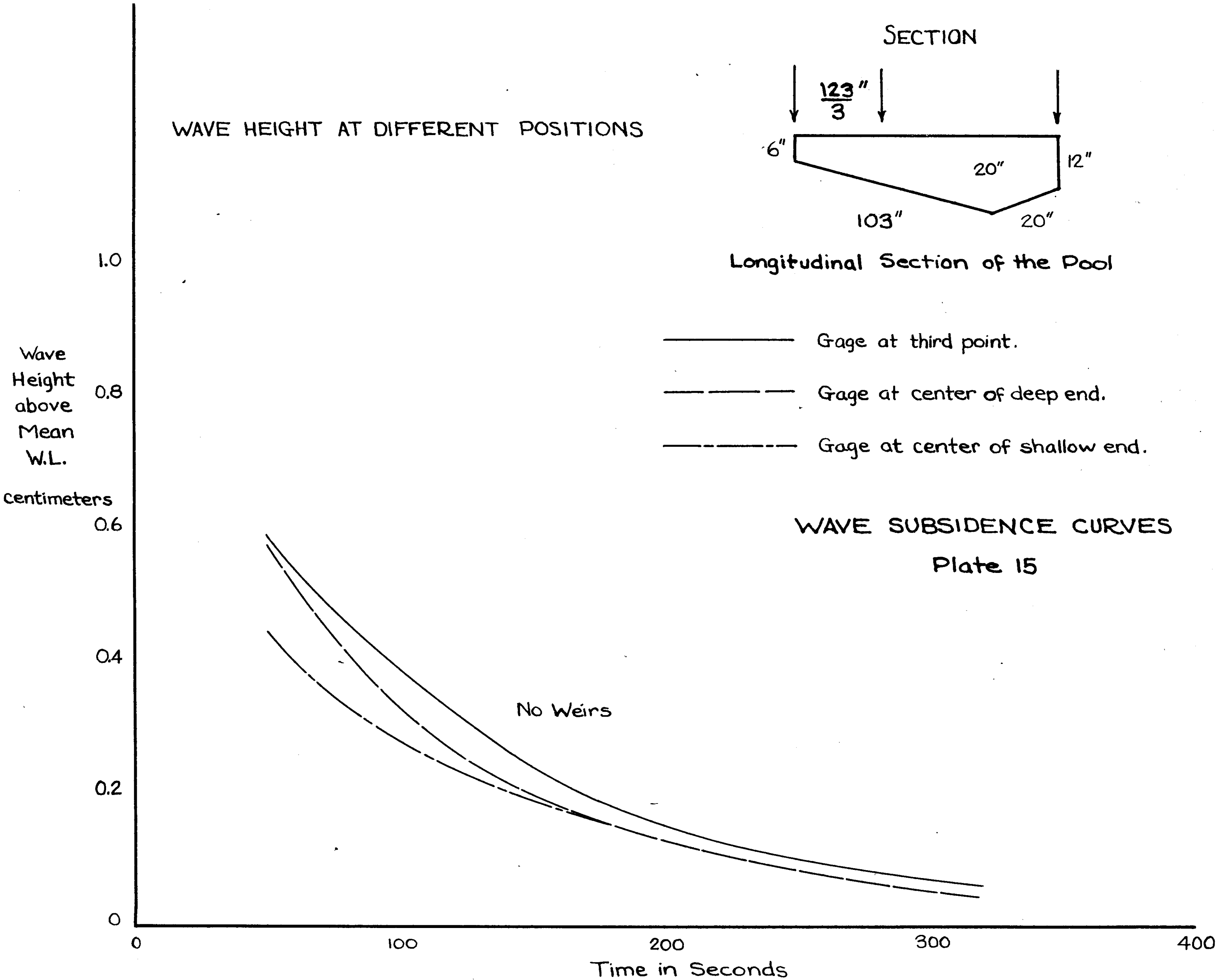
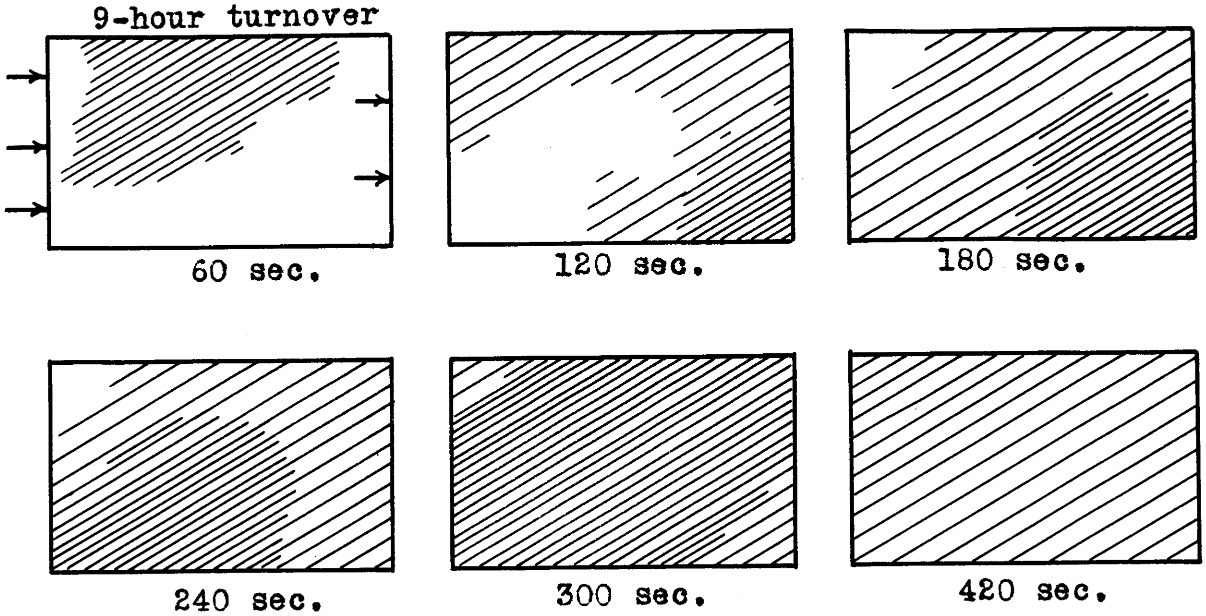

WAVE HEIGHT AT DIFFERENT POSITIONS
SECTION
123/3"
6"
12"
20"
103"
20"
Longitudinal Section of the Pool
Gage at third point.
Gage at center of deep end.
Gage at center of shallow end.
WAVE SUBSIDENCE CURVES
Plate 15
Wave Height above Mean W.L.
centimeters
1.0
0.8
0.6
0.4
0.2
0
No Weirs
0
100
200
300
400
Time in Seconds

PLATE 16

Mixing Diagrams.

9-hour turnover



Arrows indicate positions of inlets and outlets.

Time measured from opening of dye injector clip.

Pool section as in Plate 11.

16-hour turnover.

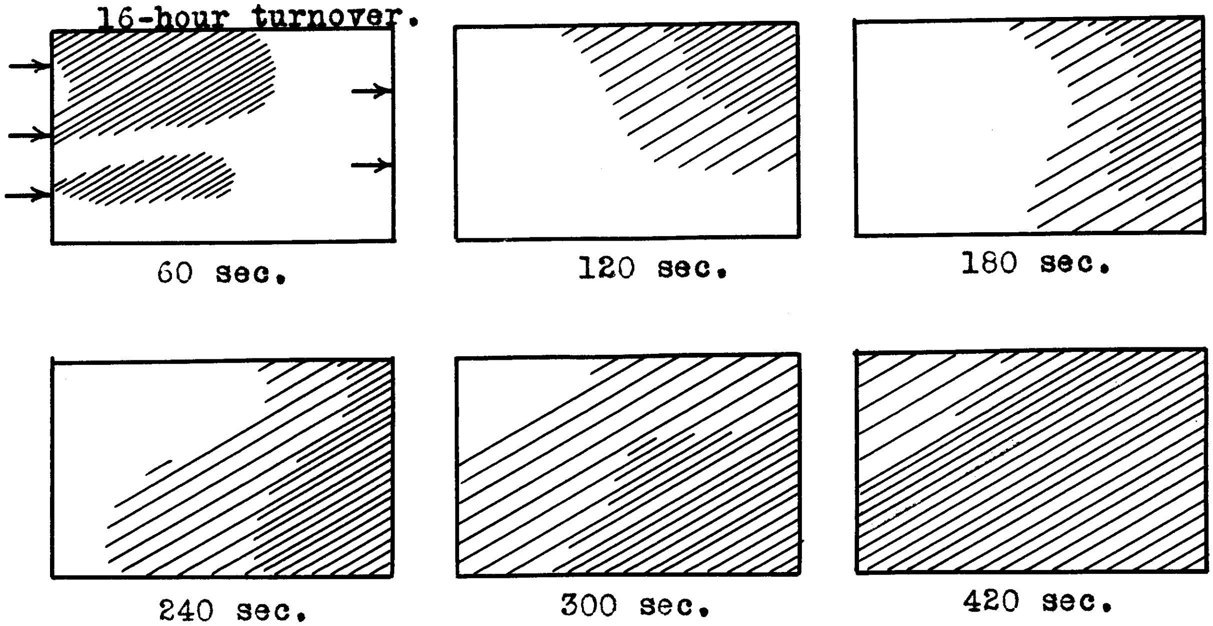
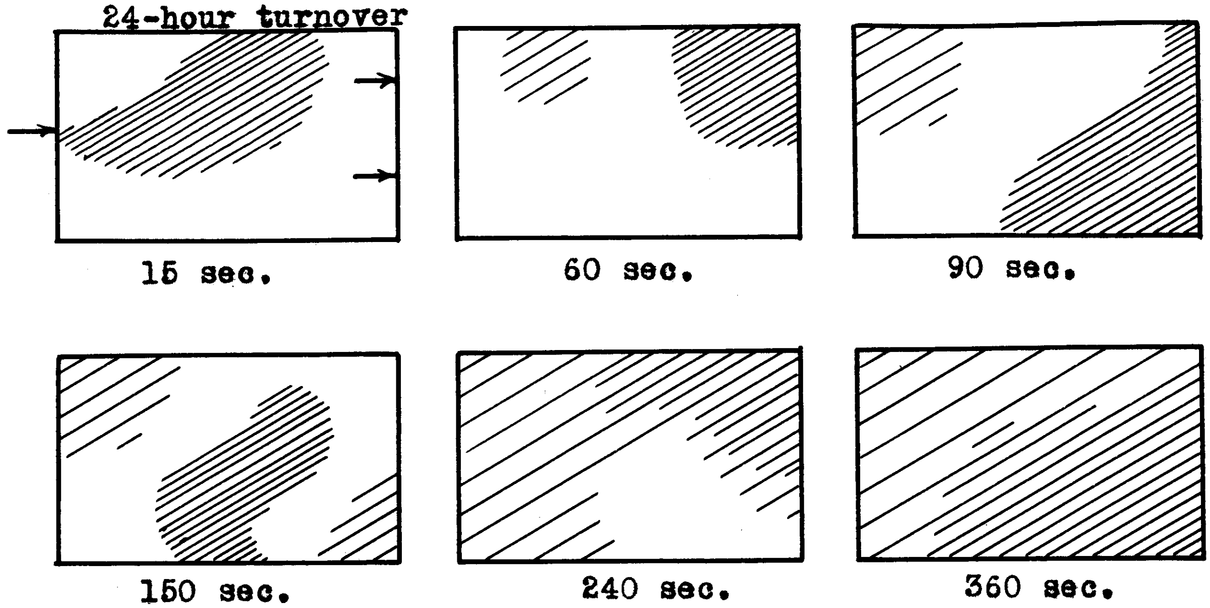


PLATE 17

Mixing Diagrams.

24-hour turnover



Arrows indicate position and direction of inlets and outlets.

Time measured from opening of dye injector clip.

Pool section as in Plate 11.

9-hour turnover

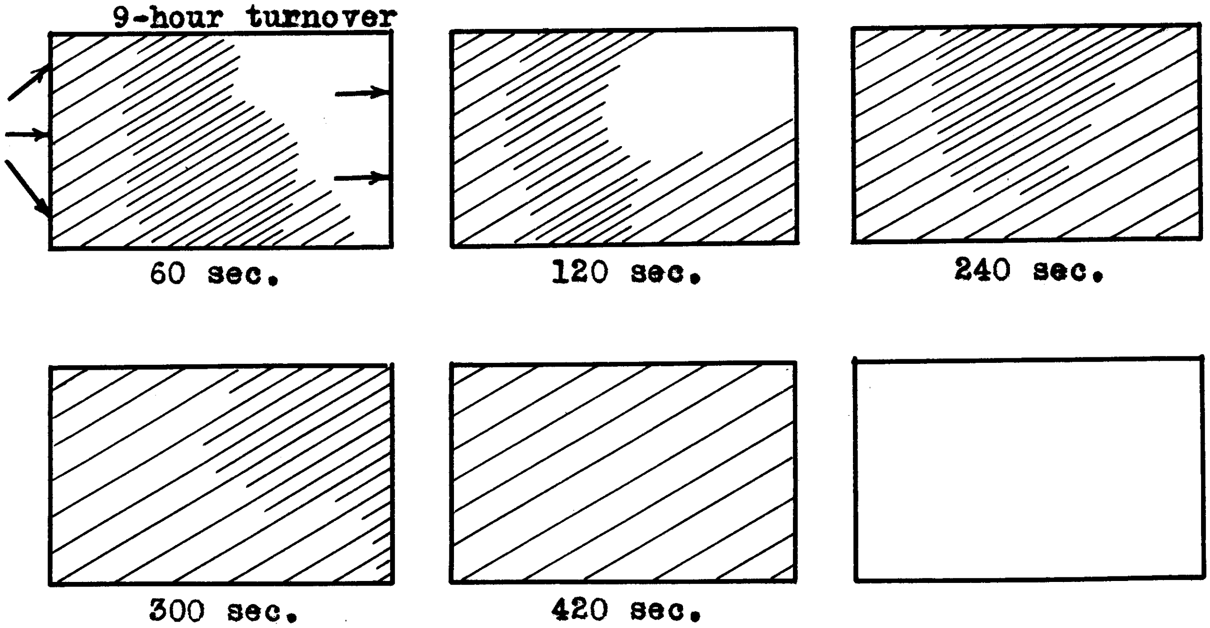
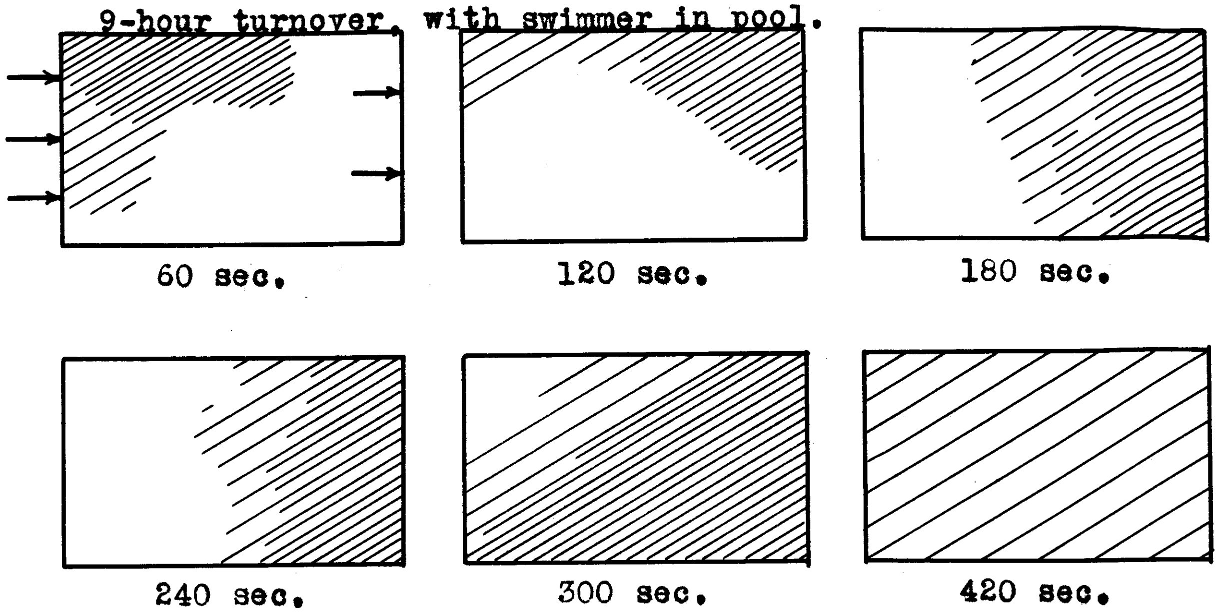


PLATE 18

Mixing Diagrams.

9-hour turnover, with swimmer in pool.

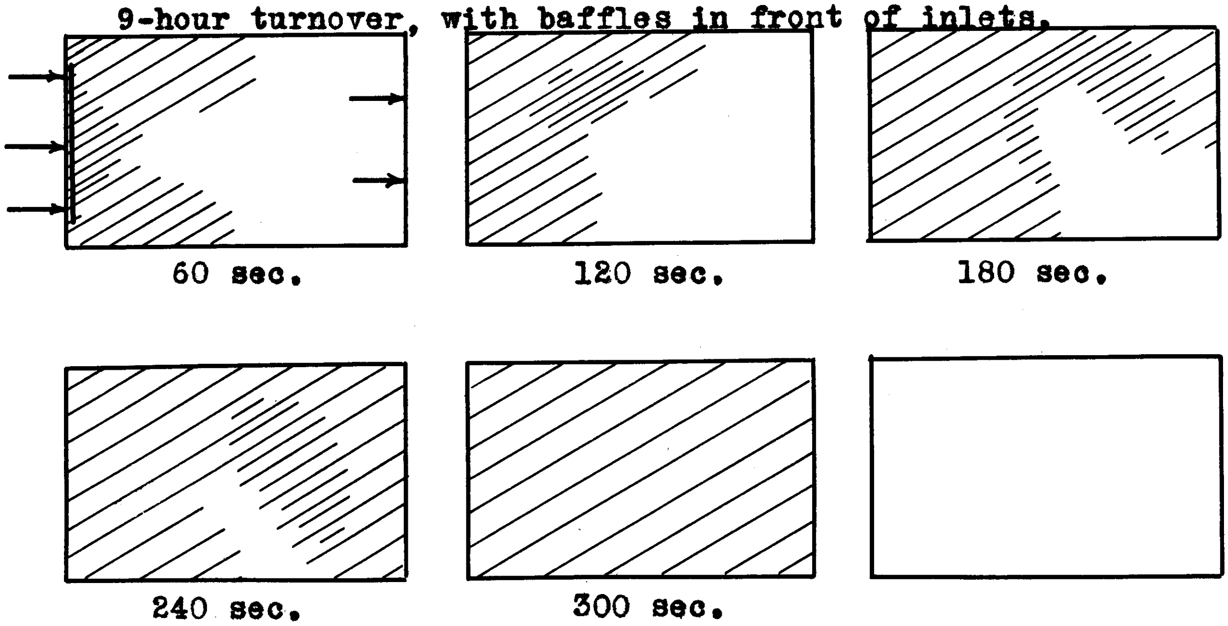


Arrows indicate positions of inlets and outlets.

Time measured from opening of dye injector clip.

Pool section as in plate 11.

9-hour turnover, with baffles in front of inlets.



PART VI

DISCUSSION

1. Experiments on Wave Subsidence.

(a) Gutter Design

Only two conditions pertaining to gutter design were investigated; and these were limiting rather than practical values. However, with a little judgment, some valuable conclusions may be drawn from the results obtained.

For each pool section the wave subsidence curve was obtained and drawn for the case of straight vertical sides with no gutters, and for the case of sharp-crested weirs over which water was flowing on the four sides. The former is undoubtedly the worst possible case, and in the opinion of the writer the latter gives the maximum obtainable rate of subsidence. The true curve of wave subsidence for a swimming pool must, then, lie between these extreme curves, which have been plotted on one sheet for each section for purposes of comparison.

After observing the action of gutters in several pools, and studying the effect of the weirs in the model, it is the writer's opinion that the optimum condition obtained by sharp-crested weirs may be closely approached in swimming pools by allowing a small quantity of water to continually flow over the lip of a gutter from which the waste water is immediately drained so that none of it is washed or thrown back into the pool. There should be no obstruction to the free passage of waves and wash over the gutter lip.

In this connection, it is important to note that a brief and simple test, previously described, showed that whether the water flowed over the weirs on four sides, on two sides only, on one side only, or on one end only, the rate of subsidence of the waves showed no appreciable difference. Practically, this means that gutters at the ends of the pool are neither detrimental nor helpful as regards to quietness of pool.

(b) Longitudinal Pool Section.

Each of plates 1 through 11 is the wave subsidence curve for one pool section under a given set of conditions. Plate 12 is a superimposed nest of these curves for each section with gage measurements made at a common point, and with all other conditions constant. Thus the curves offer a direct comparison of the rate of wave subsidence for the various sections.

Referring, then, to plate 12, certain conclusions may immediately be made.

It is obvious that the rectangular sections are the least "quiet", and that the shallower section gave by far the greater disturbance in the case where no gutters were used. No quantitative comparison should be made between these curves, as no depth - wave subsidence relation can be determined without a thorough study of intermediate and more extreme rectangular sections.

The pool with the bottom at an even slope from end to end was quieter than the rectangular (constant depth) pool of the same maximum depth, but not as quiet as either of the two sections with the bottom on a broken slope. It appears safe to state, considering the evidence given, that the preferable pool section in respect to wave action is one in which the bottom grade line is broken at a definite angle at some intermediate point. The probable accuracy of the curves is not fine enough to permit a comparison between the two sections which have a broken bottom slope. They appear to be equally quiet.

The writer anticipated the above conclusions to some degree through his visual observation, before the curves were plotted. It was noticed that in the pool with a level bottom the waves graduall decreased in magnitude; but that in the section with a sloping bottom the waves gradually decreased to a critical size, when small, choppy waves suddenly developed at the shallow end and rapidly spread over the entire pool surface, accompanied by a sharp decrease in wave size. Plate 2 illustrates this phenomenon fairly well.

It should also be noticed that, with water passing over sharp crested weirs or an equivalent type of gutter, it makes little difference which section is used. Under this condition all of the sections have practically the same rate of wave subsidence, except that the perfectly quiet condition was reached an appreciable length of time sooner in the case of a pool with a sloping bottom than was obtained for a pool with a level bottom.

(c) Lane Markers.

Swimming coaches agree that lane markers,- circular cork sections closely strung on ropes which are floated between the lanes, on the water surface - are beneficial to pool quietness. Most of the coaches interviewed believed that these markers were most effective when allowed to float loosely between their end supports.

Plate 13 represents the results of experiments performed on a "spoon shaped" section to determine the effect of lane markers.

It is quite evident that, with or without gutters, the maximum rate of wave subsidence is obtained when the lane markers are stretched tightly between the end supports. The tightly stretched markers are definitely much better than the loose ones.

(d) Wave Conditions at Different Parts of the Pool.

The rate of wave subsidence was determined at the center of each end, and at the 1/3 point nearest the shallow end along the side, for two sections. The results are shown for comparison in plates 14 and 15. While these curves have little practical application, they are of interest in that they refute the general belief, among the coaches whom the writer interviewed, that the shallow end was the roughest end of the pool. These experiments show quite definitely that the shallow end is as quiet or quieter than the deep end, or an intermediate point.

The writer will make no attempt to explain why the wave conditions at the 1/3 point are in such relative variance for the two cases. He wishes to emphasize his belief, however, that these curves are substantially correct for the stated conditions.

2. Experiments on the Mixing of Incoming Water.

Due to practical limitations these tests were made with the inlets at the shallow end of the pool only, and with the outlets at the bottom of the deep end. However, some important conclusions may be made from the results of these tests.

While visiting a local pool, recently constructed after a careful design, it was learned that in spite of a design deliberately intended to create a condition of steady flow from inlet to outlet ends, a vortex was formed which caused all foreign material to collect in the center of the pool. This phenomenon was also noted in the model pool, which had similar intake and outlet conditions. In spite of all attempts to cause the incoming water to advance steadily from the shallow to the deep end, a vortex was formed which centered approximately about the volumetric center of gravity of the section. For symmetrical intake end conditions, the vortex could be made to revolve in either direction; once started, this direction was maintained.

For given inlet and outlet conditions it was noted that thorough mixing occurred in approximately the same length of time, no matter whether the rate of flow was equivalent to a 9-hour or a 16-hour turnover.

It was noted that whether the outlet valves discharged water at the same rate as it was delivered to the pool, or whether the outlet valves were closed and all the water passed over the weirs, there was no noticeable difference in the flow, or mixing conditions within the pool, all other conditions remaining constant. This fact was carefully checked by a thorough series of comparative tests.

It has been suggested that great improvement in circulation conditions would result if the outlet drain extended the entire width of the pool at the base of the deep end. The writer believes, in view of the facts outlined above, that no benefit would result from this comparatively expensive construction. The vortex would still form, and the foreign material in the pool would continue to collect at its center.

Tests were made to determine the effect of a swimmer on the mixing of the incoming water. Some effect was noticed, but in no case was the normal pattern of flow seriously affected. In fact, the mixing was more often hindered than aided by the swimmer. The extreme case of this which was noted is illustrated by a comparison of the sketches at the top of plate 18 with those at the top of plate 16. Conditions were identical except that in the case of plate 18 a swimmer traveled up the center of the pool, against the direction of flow, just as the dye supply clip was opened.

It was suggested that baffles be placed over the intakes in order to obtain better mixing. Tests showed that no benefits would be obtained from such baffles. Either a concentration of the incoming water was obtained at the shallow end, thus making possible progressive contamination toward the deep end; or the incoming water followed the bottom very closely until carried into the vortex at the deep end, thus giving a condition of dead spots at the shallow end in which considerable contamination might result.

It was then attempted to get better results in respect to mixing by forming a double vortex. Of the three inlets, the center one was allowed to discharge normal to the end wall, while the two inlets near the sides were made to discharge toward the sides at an angle of 30° to the end wall. Noting that in all cases the incoming stream tends to avoid the central mass of water, and follow the sides, it was hoped that the pool could be divided lengthwise into two symmetrical vortices. But this proved impossible; two vortices were formed, one at the end, and one near the center of the pool. This facilitated the mixing to some degree, but not to any radically great extent.

However, it is the writer's opinion that any of the methods in which the fresh water is introduced through a series of unobstructed jets give satisfactory mixing if the turnover occurs in 16 hours or less.

PART VII

CONCLUSIONS AND RECOMMENDATIONS

1. Gutter Design.

The optimum condition of wave subsidence due to gutter design will be obtained if water is allowed to continually flow over the lip of a gutter which is so designed that the splash will be immediately drained, and not permitted to wash back into the pool. Care should be taken to avoid a design which might cause injury to a swimmer.

Further experimental work on gutter design is necessary. A study of width, depth, and back-angle of gutters as affecting their efficiency is desirable.

Gutters at the end of a pool are neither helpful nor detrimental to the wave subsidence if the section is similar to any of those treated in this report.

2. Longitudinal Section.

Shallow pools are less quiet than deep pools.

Pools of constant depth are less quiet than pools of varying depth.

Pools of constant bottom slope are less quiet than pools in which the bottom slope has a pronounced break at some intermediate point along its length. Sections similar to those shown on plates 10 and 11 are recommended as being the best studied. Further study may lead to better sections, possibly with curved bottoms.

3. Lane Markers.

Lane markers have a definitely beneficial effect on the quietness of the pool, especially if they are drawn tightly between the ends.

4. Inlets, Outlets, and Mixing of the Incoming Water.

Any conventional design calling for less than a 16-hour turnover, in which the water is delivered to the pool through unobstructed jets should give satisfactory mixing. The much talked of "dead spots" are obtained only in exceptional cases, so that expensive and complicated inlets and outlets are not necessary. However, any proposed design should be tested before adoption by a model study similar to this one.

A vortex must be anticipated revolving about a point near the volumetric center of gravity of the section. Hair and other foreign matter will tend to accumulate at this point. A drain at this point, when determined, might be beneficial, although this is pure conjecture.

Swimmers have relatively little effect on mixing. The effect is often on the detrimental side.

NOTE None of the data in this report should be used to draw qualitative results. These data are qualitatively applicable only to a precisely identical model.

PART VIII

ADDENDA

The writer made several trips to nearby swimming pools, and made notes of observations and of conversations with swimming coaches and other authorities on swimming pools.

This report does no more than break the surface of the problems relating to the hydraulic design of pools. For truly comprehensive knowledge of the priciples involved, much more experimental work is needed. Since much of the miscellaneous data may be of considerable interest to further experimenters, the writer is leaving his field notes with Professor K.C.Reynolds, so that they may be used for further reference.

REFERENCES

"The Physics of Solids and Fluids", by

Ewald, Pöschl, and Prandtl.

PART IX

ACKNOWLEDGMENTS

The writer wishes to express his sincere gratitude to Professor K.C.Reynolds, whose personal assistance and suggestions were largely responsible for the satisfactory completion of this experimental work.

The writer is also indebted to Mr. Ralph Jope, of the Technology Review staff, who suggested that this work be carried out, and who enabled him to visit many swimming coaches and pools which he otherwise would not have seen.

Thanks are also due to the many coaches and other authorities on swimming who, by conversation or letter, gave suggestions of value in defining the proper scope of this report.